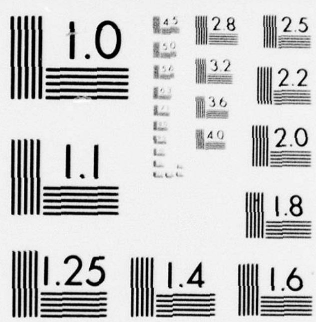
AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)
MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A

UNCLASSIFIED USCG-D-38-78 NL

1 OF 6
AD
A059891



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

REPORT NO. CG-D-38-78

STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS — PHASE I, CLOSED LOOP MODEL OF THE PROCESS OF NAVIGATION

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

MARCH 1978

FINAL REPORT

Document is available to the U. S. public through the National Technical Information Service, Springfield, Virginia 22161

~~ORIGINAL CONTAINS COLOR PLATES: ALL DDC REPRODUCTIONS WILL BE IN BLACK AND WHITE.~~

PREPARED FOR

U.S. DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD

OFFICE OF RESEARCH AND DEVELOPMENT

WASHINGTON, D.C. 20590

9590 (18) USCG

Technical Report Documentation Page

(19)

1. Report No. CG-D-38-78	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle (6) STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS - PHASE I, CLOSED LOOP MODEL OF THE PROCESS OF NAVIGATION		(11) 5. Report Date MAR[redacted]978 6. Performing Organization Code
7. Author(s) (10) W.H./Clark, A.R./Stephenson, R.H./Bateson, J.E./Jones C.G./Pohle[redacted]		8. Performing Organization Report No. (12) 521 p
9. Performing Organization Name and Address SYSTEMS CONTROL, INC. (Vt) 1801 Page Mill Road Palo Alto, CA 94304		10. Work Unit No. (TRAIS) 782703 (15) 11. Contract or Grant No. DOT-CG-75400-A NEW
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Research and Development Washington, D.C. 20590		13. Type (9) Report and Period Covered [redacted] FINAL REPORT 30 SEPT[redacted]977-29 MAR 1978 14. Sponsoring Agency Code G-DOE-4
15. Supplementary Notes		

16. Abstract

This document presents the results of a study of Aids-to-Navigation Systems in the harbor and harbor entrance environment. The objectives of this Phase I study were to develop a preliminary methodology to clearly identify the essential elements of the process of navigation, and to develop a preliminary analytical model to evaluate systems of aids to navigation.

During the course of the Phase I effort, a survey of experts in navigation, navigation research, and NAVAID system planning was completed and the current state-of-the-art in each area was summarized. The essential elements of the process of navigation were identified and were incorporated in a functioning model of the process of navigation. This model was used to successfully emulate mariner/vessel performance in real-world conditions. The mariner's requirements for navigational information were identified and the amount and type of navigational information available from aids was identified and correlated with information utilization associated with unique harbor, vessel, environmental, and visual aids to navigation system characteristics.

The form and structure of a preliminary Navigation System Evaluation Model were developed, and the requirements for model completion and validation were defined.

17. Key Words Dynamic simulation, human factors, human modeling, marine navigation, navigational accuracy, navigation systems planning, process of navigation, short-range aids to navigation	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	511	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

389 333 Gee (1) 2x (1) 2x

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The contents of this report do not necessarily reflect the official view or policy of the U. S. Coast Guard and do not constitute a standard, specification, or regulation.

COVER 2

3+4X

Cover 2

3+4X

DOT USCG STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS - PHASE I MARCH 1978
CLOSED LOOP MODEL OF THE PROCESS OF NAVIGATION

SPINE

SHOOT S/S

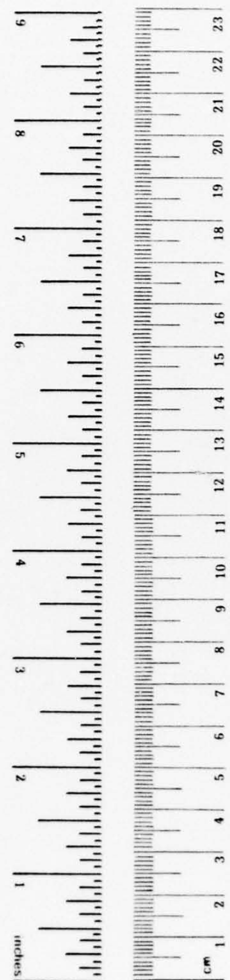
Copy for spine

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

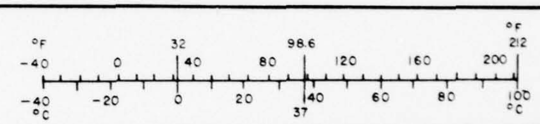
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



3 4x 3 4x

PREFACE

This work was performed by Systems Control, Inc. (Vt), a subsidiary of Systems Control, Inc., over the period of 30 September 1977 to 29 March 1978.

The U.S. Coast Guard Technical Representative was LCDR J.R. Sherrard. The Systems Control, Inc. (Vt) Program Manager was W.H. Clark. Project Manager for data base development and identification of the elements of the process of navigation was Mr. R.H. Batesen. The assessment of the State-of-the-Art in navigation, navigation research, and navigation systems planning was accomplished by Mr. C.G. Pohle. Project Manager for Navigation System Evaluation Model development was Mr. A.R. Stephenson, who was assisted by Mr. J.E. Jones and Dr. K.M. Kessler. Programming support was provided by Mr. R. Vargus and Ms. J. Mohr.

Valuable contributions from the following SCI (Vt) consultants are acknowledged: Capt. H. Breitenfeld, of the Sandy Hook Pilots Association; Dr. G. Rowland, Research Psychologist; Ms. R. Feldman, Maritime Research librarian; Dr. J. Sorensen, technical consultant; and CDR R.B. Richardson, former Harbor Master, Port of London.

Report publication efforts were coordinated by Ms. C. Walker.

5 6X

5 6X

TABLE OF CONTENTS

7 8X

7 8X

LIST OF FIGURES

9

LIST OF FIGURES (Continued)

(10)

(10)

LIST OF TABLES

11 12X

PAGES 1 THRU 511 Follows

Pages 1 thru 511 follow

1. EXECUTIVE SUMMARY

This report documents the results of a Systems Control, Inc. (Vt) [SCI (Vt)] study of aids to navigation systems in the harbor and harbor entrance environment. The objectives of this Phase I study were to develop a methodology to clearly identify the essential elements in the process of navigation, and to develop a preliminary analytical model to evaluate systems of aids to navigation. The Phase II study will involve validating the analytical model and deriving objective establishment/disestablishment criteria for systems of aids to navigation.

1.1 STUDY METHODOLOGY

The SCI (Vt) technical approach for the Phase I study was directed towards satisfying the Phase I objectives and also towards developing a methodology which can be extended directly to Phase II.

The approach focuses on understanding the process of navigation in sufficient detail that the relationships, interactions, and parameters of which the navigation process consists can be quantified. Such a quantification will enable measures (such as safety, workload, convenience, etc.) to be related to navigation aid configurations in a systematic, structured manner. In this way, meaningful establishment/disestablishment criteria can be derived, and the aids to navigation system planning will be enhanced.

Quantification of the navigation process requires a detailed understanding of how the mariner utilizes the information provided to him, and an assessment of the accuracy with which he is able to recognize, discriminate, measure, and process the information.

Such mariner performance characteristics are generally addressed by experimental procedures, ranging from the psycho-optical, to performance observations, to verbal protocols, and to large scale man-in-the-loop simulations.

Before conducting experiments, however, it is important to examine the potential impact of mariner technique and performance on overall navigation performance. Little is to be gained, for example, in quantifying the mariner's accuracy of perception of large angles off the bow, or the accuracy of certain distance perceptions, unless his performance in maneuvering and track keeping is sufficiently sensitive to these parameters. It is also important to differentiate between the mariner's assumptions concerning his ability to perceive and measure, based on learned behavior, and his actual abilities. Lastly, it is important to determine what information is used and to what degree, as a function of harbor, vessel, and environmental characteristics.

The SCI (Vt) approach was to develop the overall framework (model) which can utilize information derived from any of these experimental procedures. The result consists of a dynamic "process of navigation" model embedded in a Monte Carlo simulation framework, which permits analysis of navigation performance in any desired situation. The process of navigation model was designed to perform the same dynamic vessel positioning function which can be performed by large scale bridge simulation facilities, such as the Maritime Administration Computer Aided Operations Research Facility (CAORF) at Kings Point, N.Y. In the SCI (Vt) model, the human pilot, helmsman, and computer-generated CAORF display are replaced by an analytical all-digital mariner model. The mariner model which was developed was derived from human operator theory, and draws from previous engineering models of the human performing estimation and tracking tasks. Although it is not practical to replicate all the details of the human behavior, it is feasible to reproduce the mariner's functional performance as an estimator,

decision maker, and controller in a manner which emulates the results of his actions in response to a given situation to the accuracy required to satisfy study objectives.

The major elements of the SCI (Vt) approach include:

(1) Data Base Collection. A comprehensive data base was collected from expert interviews, literature review, facility surveys, and available simulation results.

(2) Identification of Process of Navigation Elements. Elements of the navigation process were identified from the data base and described qualitatively.

(3) Model Formulation. Quantitative relationships were formulated for the various facets of the navigation process utilizing these qualitative descriptions, drawing wherever possible from previous modeling efforts.

(4) Model Development. These quantitative relationships were then integrated into a coherent system model structure. This structure was also designed for convenient user interface.

(5) Model Application. Preliminary results were obtained by exercising the model under realistic situations.

From the preliminary results, assessments were made of the validity of the approach.

The SCI (Vt) approach primarily emphasizes fast-time simulation (rather than man-in-the-loop models) because of the significant economic advantages. Real-time experiments cannot address all of the potential situations of interest to the extent required to provide statistically significant results because costs would be prohibitive, both in terms of engineering effort and the time required for test planning, test conduct, and the analysis of results. Fast-time simulation can serve to alleviate this situation in two distinct ways:

(1) It can exhaustively test a given situation (such as harbor module, aid configuration, vessel type) and yield results almost immediately; and

(2) It can be used as a tool to identify which parameters and relationships most strongly influence navigation performance, thereby directing real-time experiments toward these sensitive areas.

In this regard, fast-time simulation can utilize and retain valuable information generated by real-time experiments by using the experimental data to "calibrate" the digital model.

Finally, fast-time simulation has the advantage of producing quantitative results. Most real-time experiments have operational deficiencies requiring subjective evaluation. All-digital experiments (simulations) are fully controlled, that is, individual experiments are repeatable, permitting detailed analyses and accurate sensitivity studies. It is always possible to determine exactly what the model did and why. Such information is essential for system evaluation.

1.2 STUDY RESULTS

The study results show conclusively that the SCI (Vt) concept is valid. The all-digital Process of Navigation model has been implemented and executed in several simulated channel situations, including a configuration similar to that used in the Coast Guard Phase IIIB restricted waterway tests at CAORF. The SCI (Vt) simulation model produced reasonable results under a sufficiently varied set of conditions to conclude that the modeling approach presents a negligible technical risk for utilization as an evaluation tool in Phase II.

The following sections summarize results related to the definition and categorization of the elements of the navigation process, and the development and preliminary application of the Phase I model.

1.2.1 Elements of the Process of Navigation

The process of navigating a vessel into or out of a harbor involves a decision making process to which the following elements all contribute:

(1) A priori information and learned behavior

(2) Situation definition and equipment availability

(3) Information available from aids

(4) Perceived mariner requirements

The first three elements constitute inputs to the Process of Navigation model. Mariner requirements (in terms of accuracy, information availability) are used in the overall system evaluation model as a basis for comparative analysis. A priori information is that obtained or derived prior to commencement of a transit, such as tide, docking or undocking time constraints, visibility, anticipated traffic, anchorage information, local procedures, intended channels, and aid discrepancies. Learned behavior has a significant impact on the ability to navigate safely, and includes items such as turn rate judgments, discrimination between angular observations, sensing of bank suction, and ability to estimate distances. Certain operational situations are also defined for use in the model structure, as is available equipment. These factors are those over which the mariner has essentially no control; for example, vessel design, placement of aids to navigation, environmental conditions, etc.

The process of navigation employed in a specific situation is highly dependent upon the information available from aids. The basic approach taken was the specification of variables suitable for modeling; this involved the identification of measurable or "perceptable" information in the form of distances, distance differences,

angles and angle differences. Depending upon the basic aid configuration, a perception of the relative value of any or all of these variables was then translated into necessary information required to maintain a defined track line within the specified harbor module. The navigation process then deals with the overall selection of a route which involves a series of guidance and control strategies (tasks). The mariner's process of navigation consists of a hierarchy of navigation, guidance, and control phases conducted simultaneously with visual search, recognition, and monitoring operations. The mariner is the operative element in the process; he adapts and manipulates his dynamic characteristics to satisfy the key guidance and control requirements for the mariner/vessel closed-loop system.

There are three general levels of control behavior of the mariner in the process of navigation. These levels are precognitive (a learned maneuver executed in an open-loop manner); pursuit (relying on preview information, upon which the mariner takes advantage of knowledge of future system input, to structure a control strategy) and compensatory (or regulation, which implies an operation on a perceived error between actual motion and desired motion). The specific functions performed by the mariner can be categorized into an estimation function, a decision function, and a control function. His actions are either as a (passive) monitor, or (active) controller. The way in which the mariner performs these specific functions is highly dependent upon the situation in which he finds himself, i.e. the physical and environmental conditions. The modeling of the process of navigation is based on an analytical emulation of the mariner's estimation, decision, and control functions as applied to the particular situation and navigation aid configuration of interest.

1.2.2 Navigation System Evaluation Model

The elements of the process of navigation as described above were formulated into mathematical relationships. Models were developed (which are stochastic in nature) to describe the procedure of estimating vessel position, velocity, and orientation using distance and angle measurements with respect to the aids to navigation. These models account for uncertainties in distance and angle perceptions, and also include the effects of environmental disturbances. Models were also formulated to represent the mariner's decision making process and control strategies, drawing in part from prior work in human operator modeling technology. These individual model elements were integrated into a coherent structure, which is called the Navigation System Evaluation Model (NSEM). This structure facilitates user input and enables computation of statistical relationships between aids to navigation configurations and navigation system performance measures.

1.2.3 Preliminary Model Application Results

Simulation test cases were designed for three harbor modules: a straight channel, and two types of bends -- regular and truncated. Three buoy configurations were analysed for each module: one mile gated, two mile gated, and one mile staggered. Channel width was 800 feet, and the CAORF 80,000 ton tanker was simulated at a speed of 8 knots for single-run bend configurations and all Monte Carlo runs, and at 12 knots for straight channel single-runs. The purpose of the single runs was to permit a model component analysis to examine representative performance of the estimation and decision/control components of the mariner model, to select nominal parameter values for the respective components, and to make preliminary assessments of the model's sensitivity to these parameters and to situation geometry.

The purpose of the Monte Carlo runs was primarily to assess vessel track-keeping performance. In all cases, model performance was essentially as expected. The simulation results exhibited reasonable correlation, in terms of anticipated and actual measurement errors, vessel control, and track-keeping performance, with expected real-world performance and recent CAORF simulation results. A detailed description of the simulation test plan and a comparative analysis of the test cases are presented in this report.

1.3 EFFORT REQUIRED FOR PHASE II

The purpose of the development of a functioning Navigation System Evaluation/Process of Navigation Model in Phase I was to demonstrate the viability of the overall modeling approach. Past experience has indicated that the successful development of detailed model and software designs does not necessarily ensure successful (i.e. validatable) model performance. This is particularly true in state-of-the-art human/dynamics modeling. Thus, far more than a design activity was undertaken. It was desirable to produce a functioning model in Phase I so that the feasibility of a model as a design tool could be demonstrated. Of far more importance in the overall (Phase II) program is the completion of the development of a methodology for navigation system evaluation which can be applied in a practical, straight-forward manner.

The primary utility of the process of navigation model lies in its ability to produce a large quantity of practical, usable results <u>during</u> Phase II, which can be cataloged as an integral part of the overall Navigation System Evaluation Model. In this manner, straight-forward criteria for aid to navigation system planning can be developed as a primary output of the Phase II effort. These criteria should include not only appropriate establishment/disestablishment guidelines, but should provide for transitional planning to ensure user acceptance. It is essential that the

Coast Guard be able to demonstrate a correlation of model results to real-world situations. The remaining effort, to be accomplished in Phase II, can be categorized as follows:

(1) Incorporation of additional model capabilities

(2) Expansion of the study data base

(3) Model validation from experimental data

(4) Application of the methodology for the derivation of establishment/disestablishment criteria

(5) Documentation of the methodology and implementation of the model for USCG use.

1.3.1 Model Extension

Some degree of modification will be made to the model to enhance its usability as a Phase II analysis tool. Part of the effort will address facilitating input/output and USCG user interface. Additional aids to navigation system evaluation capability must also be incorporated in the model, including radar and radio aids, as well as the provision for accommodating traffic. Vessel dynamics and characteristics will be expanded to include additional vessels, throttle dynamics with engine response and vessel speed, and other dynamic effects as required.

1.3.2 Data Base Expansion

The navigation data base established for Phase I contains sufficient information to establish the essential elements of the Process of Navigation; this enabled initial model development. The data base is also sufficiently broad to enable Phase II to commence in a timely fashion

Additional data will be required in the areas of vessel characteristics, mariner performance levels, aids to navigation, and local practices. It will also be necessary to examine a large number

of harbors for the purpose of identifying a more complete set of harbor module/situation/aid configuration combinations for analysis in Phase II, to ensure the universality of the system planning criteria which are to be developed.

1.3.3 Model Validation From Experimental Data

Phase II activities will focus on the validation and calibration of the model utilizing experimental data, to ensure that the Process of Navigation model and the navigation system evaluation procedure will produce performance measures that are valid and useful to the Coast Guard in assessing aid to navigation needs. The methods followed to validate the model can be categorized into two different activities; sensitivity analyses and validation via experimentation.

One purpose of the sensitivity analysis is to exercise the model with various parameter values to determine (a) sensitivity of output performance measures to model parameters and (b) the structure of the experiments. Another type of sensitivity analysis involves using experimental data to determine model parameter values. For example, in a wheelhouse simulator (such as CAORF), the cross track position can be changed at a given location along the channel to determine the impact on the pilot's ability to estimate cross track position. Similarly, the position of the buoy pair downstream may be varied to evaluate its impact on the pilot's estimates of his along track position. This type of static error (quantified by mean and standard deviation) is a function of actual vessel position in the channel. These statistical quantities are then used to set values of parameters in the model.

Validation experiments are designed for the purpose of (a) verifying that the results of the model sensitivity analyses are correct, (b) discovering new phenomena that need to be

incorporated into the model, (c) determining values of key model parameters and how they vary with a changing scenario, and (d) spot checking the validity of the model's predicted outcome (performance measures) at specific operation points. The types of validation experiments will include the following:

(1) Additional interviews and/or ship riding observations to expand and verify the "information used" data base;

(2) Static psycho-optical perception experiments utilizing static displays, interactive TV graphics, and simulated real-world displays, such as that available at CAORF, for the purpose of quantifying the mariner's assumed and actual perception errors;

(3) Man-in-the-loop dynamic simulations at CAORF for the purpose of validating track keeping performance and its relationship to those behavioral and perception parameters which have been determined to be of importance and which can be measured in these simulations.

The results of previous experiments of similar type will also be utilized for model validation.

1.3.4 Establishment/Disestablishment Criteria Development

One of the most important Phase II activities will be the utilization of the completed and validated model to establish aids to navigation system configuration design criteria. This will include extensive documentation of aids to navigation system establishment/disestablishment criteria as a function of desired and achievable safety and traffic facilitation measures, including accident probability and mariner workload considerations.

Inherent in the Phase II objectives, whether stated or implied, is ultimate acceptance by the mariner of changes in an aids to navigation configuration which have been derived on the basis of model execution. In order to ensure mariner acceptance, the manner

in which the Navigation System Evaluation Model is utilized must be carefully structured, including, as a minimum, the following considerations:

(1) Transitional (phased) disestablishment criteria, from the viewpoint of implementation feasibility as well as user acceptance

(2) Consonance with predeveloped mariner concepts

(3) Use of real-world situations as examples

There is little doubt that mariners will accept the criteria developed to add a single or small number of aids to an existing configuration. Interviews with mariners and with Coast Guard personnel indicate that this is a common practice today.

The disestablishment of aids is a much more difficult task, even for a single aid. Frequently the history of its original establishment rationale is not available. Special interest groups may be involved but not known. Time consuming hearings may be needed, with the acceptance of the criteria being partially dependent on opinion and conjecture.

Since there is no reason to believe that the political problems involved in aids to navigation configuration management will change, the criteria developed in Phase II must be sensitive to these conditions. In essence, this means that when a final configuration has been selected, it must include the incremental changes which may be required to arrive at the final configuration.

1.3.5 Coast Guard Utilization

A primary purpose of the aids to navigation system evaluation methodology is to derive standards and criteria which may be published by Headquarters for district use. The model which is delivered to the Coast Guard must be capable of use by Headquarters WAN personnel with a minimum of training and with a minimum of

operator input/interface requirements. For this reason, SCI (Vt) devoted a portion of the Phase I effort to a preliminary analysis of operator interface requirements. This analysis will be expanded in Phase II. From the results of the preliminary analysis, it was determined that the Navigation System Evaluation Model can be effectively implemented as an interactive graphics system.

SCI (Vt) will establish the Phase II model on the selected computer system and provide supporting documentation in the form of:

(1) Commented listings of the model and support routines;

(2) Flowcharts of all but the simplest subroutines; and

(3) A user's manual.

The model will be demonstrated for USCG acceptance, and USCG personnel will be instructed in its use.

1.4 SUMMARY AND CONCLUSIONS

During the course of the Phase I effort, SCI (Vt) completed a survey of experts in navigation, navigation research, and aids to navigation system planning and summarized the current state-of-the art in each area. The essential elements of the process of navigation were identified and were incorporated into a functioning model of the process of navigation. This model was used to successfully emulate mariner/vessel performance in real-world conditions. The mariner's requirements for navigational information were determined; the amount and type of navigational information available from aids was identified, and this information was correlated with unique harbor, vessel, environmental, and visual aid system characteristics.

The form and structure of a preliminary Navigation System Evaluation Model was developed, and the requirements for model validation were defined.

From the results of the SCI (Vt) Phase I study, it is concluded that the application of fast-time simulation techniques to the evaluation of mariner/vessel performance is feasible. This methodology provides the overall framework for (a) design of simulator and operational experiments as well as utilization of all experimental data effectively, (b) the assessment of aid to navigation system requirements for a broad range of situations in an expeditious and cost-effective manner, and (c) the determination of quantitative criteria for the establishment/disestablishment of systems of aid to navigation.

II. TECHNICAL APPROACH

2.1 INTRODUCTION

The U.S. Coast Guard has undertaken a multiple year effort whose overall goal is to develop a quantitative approach for designing and evaluating systems of aids to navigation to meet user requirements, minimize risks to safety, and enhance expeditious passage. The specific objective of this Phase I effort is to obtain a structured approach and a preliminary methodology to meet the above goal. Any such approach must be capable of relating aid to navigation performance measures (such as safety, workload, and convenience) to aid configurations (such as type, location, information content) in a systematic, structured manner such that meaningful establishment/disestablishment criteria can be derived and thus the aid to navigation system planning/design process can be enhanced.

The scope of the overall effort includes both audio-visual and electronic aids and waterways within the U.S. The first phase has concentrated on visual aids to navigation and harbor or channel environment.

The key problem in developing a methodology for evaluating systems of aids to navigation is that the process of navigation (including the mariner's behavior) must be quantified. Thus the principal elements in the process of navigation must be identified and their interrelationships understood. Such elements include the waterway and aids to navigation configuration, the vessel characteristics, the information available from the aids, effects encountered (such as winds, tides, and currents) and the mariner's behavior (typically, the "mariner" for a large ship maneuvering in a restricted waterway includes a pilot and a helmsman). Quantifying the behavior of the mariner as he perceives information from

aids, utilizes past experiences, makes decisions, and issues commands to the vessel, is clearly the most difficult part of the project.

This section describes the rationale for selecting the SCI (Vt) technical approach and describes this approach which has been carried out in Phase I.

2.1.1 Rationale for Selection of the SCI (Vt) Approach

There are several approaches which could be followed in order to quantify the process of navigation and relate aids to navigation configurations to performance measures (such as safety and traffic facilitation). The variability of these approaches ranges from totally experimental to totally analytical.

One approach would be to physically change the aid configuration (location, accuracy of information, etc.) and note the effects on vessel movement (cross track and along track position) and safety. With the large number of vessel types, aid configurations, harbor characteristics, etc., this is clearly not feasible.

An alternative approach would be to simulate with a digital computer program, all elements such as vessel motion, aid to navigation configuration, etc. with the exception of the mariner. A study of this form could be conducted using the CAORF facility at Kings Point. Again, however, the large number of variations in the elements of this process, which are necessary to understand the process of navigation for all possible cases, makes this approach prohibitively expensive and time consuming.

A third basic approach is to quantify all elements of the process of navigation analytically and simulate the entire process using an offline digital simulation. This approach, if it can be accomplished, is the most cost effective, can be carried out in a minimum amount of time, and provides the easiest mechanism for controlling the parameters which determine cause and effect.

The requirements of the aids to navigation study which provide the rationale for selecting the SCI (Vt) approach include:

(1) Cost of replicating the process of navigation

(2) Ability to make simple changes to key parameters

(3) Ability to describe the physical process with sufficient accuracy to achieve the goals of the study

(4) Ability to establish statistically significant relationships between aids to navigation configurations and accuracy of navigation

(5) Ability to validate the approach (model) with real data or other sources of simulated data, e.g. CAORF

(6) Ability to "control" all the parameters which relate cause and effects.

The ultimate objectives of any methodology, analytical approach or model used to describe a physical process are:

(1) to be able to understand (to the required level of detail) the cause and effect relationships, and

(2) to be able to use the model (once it has been developed and evaluated) to predict performance in situations or conditions other than those for which the data was collected.

The above rationale has led SCI (Vt) to an approach which includes:

(1) the use of an offline digital computer fast-time simulation (the code for which can be included in an interactive/graphic display system for Coast Guard use) to describe the overall structure of aid to navigation evaluation process and the process of navigation;

(2) the development of the process of navigation model based on interviews with mariners, observations aboard ship, and experience of mariners on the SCI (Vt) staff (including one senior Sandy Hook pilot);

(3) use of the SCI (Vt) process of navigation model to design validation experiments in Phase II, and to collect additional data as necessary to validate the model;

(4) provision for incorporating real or simulated data in the process of navigation simulation.

The SCI (Vt) approach and resulting model can be thought of as a fast-time offline version of CAORF with the CAORF experimental subjects (mariners) replaced by a digital mariner model.

The large number of elements in the process of navigation, each of which may assume a wide range of values in the complete evaluation of systems of aids to navigation, clearly precludes basing this methodology exclusively on the use of real data. Also, for the same reason, a fast-time digital simulation is clearly required by the Coast Guard at the end of Phase II of the aids to navigation project. The use of a real-time man-in-the-loop simulator (such as CAORF) to evaluate all systems of aids to navigation is prohibitive because of cost, the time to evaluate different waterway locations, vessels, aid configurations, etc. and difficulty of Coast Guard personnel interacting with the simulator. Thus, the real "choice" becomes one of

(1) first collecting experimental data from CAORF, shipboard data, or a simplified man-in-the-loop simulator, and then to quantify this data in the form of a model;

(2) first developing the overall model structure in the form of an offline fast-time digital simulation and then using this model to "design" additional experiments (both CAORF and shipboard data collection), and validate the model subelements using experimental data (e.g. for the human operator "mariner's" model).

SCI (Vt) has chosen the latter approach. This approach, although limited in previous maritime applications, has been found to be the most successful for other man/vehicle interface evaluations. Other applications such as pilot/aircraft performance, driver/vehicle evaluations, and human operator/weapon systems evaluations have successfully used this approach. The principal reason is that by first developing a model using physical principles and qualitative descriptions of a physical process, the sensitivities of system

performance to individual model elements can be determined and used to design meaningful experiments. By conducting experiments first and then developing a model, it is generally found that meaningful data is not collected and the experiments have to be repeated.

2.1.2 Summary of SCI (Vt) Technical Approach

The SCI (Vt) approach for the Aids to Navigation System Study was guided by the two preliminary objectives of Phase I., i.e. the definition of the process of navigation (PON) elements and the development of a model methodology which would ultimately achieve all of the Phase II objectives. This approach, as summarized in Figure 2.1, contains the following major efforts:

(1) establishment of a data base,

(2) identification of the process of navigation elements,

(3) development of Navigation System Evaluation Model, and

(4) utilization of the model.

The identification of the process of navigation elements and the development of a Navigation System Evaluation Model are the main objectives of this phase. The establishment of the data base provides inputs to identify the process of navigation and formulate the process of navigation model. The final step, utilization of the model, shows the feasibility of the model developed in Phase I, indicates how these results are used for establishment/disestablishment criteria and shows how the Phase I model and results can be extended in Phase II to achieve the overall project objectives.

A proper balance of effort had to be applied to these groups to demonstrate that the SCI (Vt) approach was feasible and precisely defined. In addition, the long-term effort of Phase II requires a sufficient data base, augmented by the Coast Guard and MARAD CAORF experiments, to ensure that Phase II can be completed in a timely and productive manner.

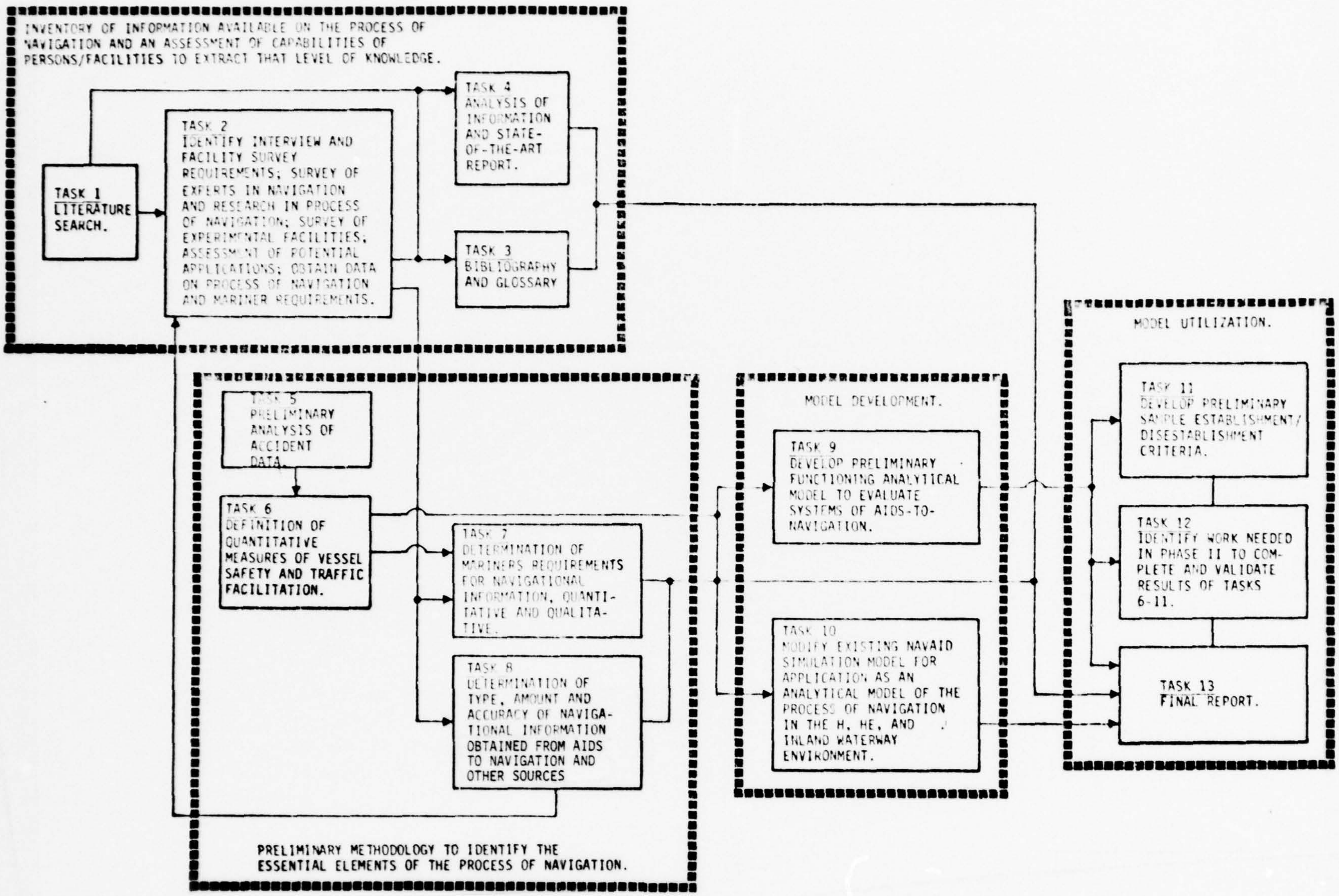


Figure 2.1 SCI (Vt) Approach to Performance of Aids-to-Navigation System Study

No significant departures have been made from the original approach proposed to the Coast Guard by SCI (Vt). Minor schedule changes have occurred. Specifically, a more complete data base was developed prior to initiation of the model development. This schedule departure was followed to ensure that the process of navigation elements were identified properly and the overall qualitative description of all processes of navigation were obtained prior to developing the model.

2.2 DATA BASE DEVELOPMENT

The primary objective of the data base development was to collect sufficient information so that all of the elements of the process of navigation could be identified. Because the "process of navigation" is somewhat unique for each transit, a singular description of the process is not possible. Hence, the process of navigation must be defined on the basis of all information elements which are available for use and processed by the mariner.

The problem then is one of determining the proper elements for each transit, the effect of the elements on the mariner, and his response to these elements and the changes as the transit progresses. To accomplish these objectives, experts in the field of maritime operations (masters and pilots), system planning and administration, and systems research were interviewed. Attempts were made to quantify the information obtained, or to obtain qualitative expressions where quantification could not be ascertained.

2.2.1 Expert Interviews

SCI (Vt)'s approach to the interviews of experts was to divide the task into areas of expertise which included:

(1) Users of the waterways as operational experts in the process of navigation

(2) Researchers, as experts in various subelements of system concepts, human factors, etc.

(3) System planners

The interviews with operational experts were concentrated in the Northeast Corridor from New York to Norfolk. These areas were selected due to:

(1) A diverse combination of aid configurations, both intra- and inter-port

(2) Familiarity of the interviewer with the areas

(3) The proximity to the Washington, D.C. SCI office.

A second group of interviews was conducted in the United Kingdom. This set of interviews was selected because of the use of VLCCs, and extensive VTS coverage. Neither VLCCs or VTS are extensively used in the United States, particularly in the Northeast Corridor.

Because the main emphasis of Phase I concerned deep draft vessels in restricted channels, the majority of interviews were with pilots and licensed masters of larger vessels. However, casual interviews were conducted with masters of smaller vessels such as municipal tankers and tugs as well as a few recreational boatmen.

Research interviews included personnel involved in human factors experimentation and analysis, requirements analysis, and operational procedures experimentation. These interviews were conducted in the USA and Europe, were unstructured, and were based upon information gained from published material and other references.

To assess the current level of system planning utilized for aid establishment and disestablishment, expert interviews were conducted in the USA and the United Kingdom. Coast Guard military and civilian personnel were contacted in the 3rd and 5th Districts and at USCG Headquarters. The primary contacts in the U.K. were Trinity House and the Thames River Port Authority. Additional information concerning electronic aids to navigation systems was obtained for several European continental ports.

2.2.2 State of the Art Report

A large amount of the information in the data base was compiled as a State of the Art (SOA) Report which covered the present day status of aids to navigation system utility, planning, and research. This report was based on the interviews of experts, review of published studies, and visits to facilities involved in navigation research, operational training and human factor analysis.

2.2.3 Preliminary Accident Analysis

A preliminary review of commercial vessel accidents was conducted, concentrating on areas in the Northeast Corridor. The objective of this review was to determine where accidents frequently occurred, under what conditions, and whether or not a specific type of harbor module or aid configuration was a potential causative factor.

To review the accident data, a computer sort of USCG Commercial Vessel Casualty data was conducted to separate accidents where vessel grounding occurred and operator judgements were considered a possible causative factor. This broad category was further reduced by eliminating accidents which would not be included in the PON evaluation, such as docking and undocking with tugs. The final list was obtained by limiting the review to those accident cases which were contained on microfilm records. Each case was then read and notations made of the accident situation and scenario.

The results of this analysis influenced the types of questions developed for the semi-structured interviews of operational experts and also gave a base for evaluating the initial model runs.

2.3 IDENTIFICATION OF THE PROCESS OF NAVIGATION ELEMENTS

To describe the elements which are a subset of the process of navigating a vessel through a restricted waterway in a harbor, the data base was examined and subdivided into several categories. These categories included the physical characteristics of the waterway, the vessel, the environment, and the tools used in navigation. Parameters involving the information available from the aids to navigation and other sources were analyzed based upon physical installations and the mariner's perception of the aids. During the course of the data collection tasks, an important element concerning a priori knowledge was recognized. To focus on areas of potential problems in navigation, the accident data was reviewed to ascertain whether or not any common areas could be uncovered.

To limit the conditions which the process of navigation was to embrace, a specific assumption was made that a safe transit was one where no emergency maneuvering was required due to an aid or waterway configuration, and that very hazardous waterways such as the reaches between Staten Island and the New Jersey shore would not be analyzed. A situation such as this was considered to be a continuous docking or undocking procedure with the use of tugs.

To catalog the process of navigation elements, they were classified as sets of situations which consisted of all the possible items in one category, i.e. a situation set is a group of vessels in a variety of harbor modules. A situation was defined as a specific vessel in a specific harbor module under a given environmental condition.

To minimize the number of situations which are processed within the module, each situation set or element thereof was examined with respect to its neighbors. Where distinct commonality existed, they were grouped under one heading.

2.3.1 A Priori Information

The data base, mainly the information developed from the user interviews, was examined to ascertain the type of information desired or necessary for the mariner to possess prior to entering the waterway. Since this information was related either to the aids, vessel, environment, or the mariner estimation of a situation, it required review to see if it would be encompassed by the model or if it must be a model operator input. This information also established whether or not the model would consider the selected parameter, i.e. color or aid discrepancies.

2.3.2 Constant Parameters

The situation set parameters over which the mariner has no control are those involving physical characteristics. These were cataloged and described. They included areas such as:

(1) harbor modules

(2) vessel maneuvering parameters

(3) aid configurations and charts

(4) environmental modifiers.

Each of these areas was characterized in terms of its known and unknown parameters, and also those which could be changed by persons other than the mariner. This resulted in a very large catalog of situations, and by virtue of the large number, revealed that modeling of all possible situations was impractical. Thus, the next step in the approach was to find common groupings of harbor modules and aid configurations.

Since vessel maneuvering capability grossly affects the ability to conduct a safe transit, a description of types of vessels and their characteristics was obtained from the SCI (Vt) pilot consultant. His description of these types is given in Table 2.1.

2.3.3 Information Available

Based on examination of charts, interviews with mariners and the experience of SCI (Vt) staff members, it was decided that information available from aids to navigation fell naturally into the following three categories, each of which corresponds to a specific use of the aid in the process of navigation.

(1) Message. The message imparted by an aid to navigation is a function of a unique characteristic and/or location. The color red is a message bit, for example. The shape of a can buoy as opposed to that of a nun provides a message of lateral significance. A wreck buoy provides a vessel with a warning.

(2) Positon Fixing. Aids to navigation are fixed reference points. Even those with no explicit message (no lateral significance) form a fixed reference frame within which the instantaneous position of the ship may be identified. The position information may be relative (i.e. identified with respect to a local reference (channel, desired track line) or referenced to a geographic coordinate system (latitude /longitude, range and bearing to a known geographic route).

(3) Guidance. A configuration of aids, usually with lateral significance, may serve to define a safe track or mark the boundaries of safe water and hence provide recommendations with regard to the navigation process. Such a configuration, when combined with instantaneous relative positioning within the configuration, and with conditions of vessel heading and speed, provide the most definitive form of navigation information.

Parameters unique and common to the three classes of information were identified for application as controlling elements in the process of navigation.

Table 2.1
Vessel Characteristics

CHARACTER-ISTIC	DWT	TYPE	LOA	BEAM	L DRAFT	GROSS TONS	NAME	COMMENT
VERY GOOD	40,933	Tank	715	93	39	23,700	Exxon Washington	The best
	80,030	Tank	818	125	44	37,200	American Sun	Excellent response
	66,500	Tank	784	105	44	36,400	Ralph Johnson	45° rudder under 8 knots
	?	Cont	689	105	35	32,200	Stuttgard Express	Bow thruster, fast response
	35,020	Cont	858	106	39	39,500	Verrazano Bridge	O.K. in wind
GOOD	27,602	Jumbo T2	634	74	35	14,700	Fort Worth	Backs slower than T2
	27,651	Cont	946	105	35	41,100	Sea Land Gallaway	Handles fair in wind
	31,991	Tank	560	86	36	19,500	Thomas Q	Good for era (1951)
	13,969	Roro	700	92	28	15,100	Portaleza	Difficult in wind
	30,665	Tank	655	82	34	17,500	Sasstown	Short of power
POOR	49,062	Tank	722	97	39	26,000	Phoenix	Poor backing
	19,050	Cont	686	88	31	22,300	Malmros Monsoon	Poor course keeping
	13,138	Cont	557	83	27	9,700	Seatrain Louisiana	Shears in deceleration
	36,510	Tank	685	86	36	22,400	Theodorus C	Poor course keeping
	22,225	Cont	700	90	32	18,700	American Legion	Poor turning

2.3.4 Information Utility

Assuming that certain types of information are available from specific aid configurations, and that the environmental modifiers of wind and current are known, a determination was made of which type(s) of information would be used by the mariner. As an example of the priority in which the mariner would select and use the information, several hypothetical vessel transits were recorded on tape. This tape, in conjunction with the appropriate charts, were used by members of the SCI (Vt) staff as an aid in preliminary model

development. Next, numerous aid configurations for four different harbor modules were depicted in a table. This table described initial conditions, selection of information sources as a means to determine vessel position, selection of information sources or rate of change of information for vessel guidance, and finally, utilization of information criteria to initiate turns.

Utilization of this information was necessary to determine the vessel conditions which were related to cross-track, along-track, and other vessel states, and led directly to the development of inputs to the Navigation System Evaluation Model.

2.4 NAVIGATION SYSTEM EVALUATION MODEL

2.4.1 Overview

The objective of the overall Phase II Aids to Navigation Study is to derive establishment/disestablishment criteria for various aids to navigation and to provide the Coast Guard with the capability to revise and/or re-generate these criteria as future needs dictate. The Navigation System Evaluation Model, including its Process of Navigation submodel, is the fundamental tool by which this objective can be met.

Despite the fact that the Navigation System Evaluation Model and the Process of Navigation submodel are integrated into what is ostensibly a single entity, these models differ significantly in terms of purpose, form and structure, and the associated rationale by which they were conceived, designed and implemented. The discussion of the SCI (Vt) modeling approach will therefore be presented in two parts. The approach toward the development of the Process of Navigation submodel is presented in the following

subsection. In Section 2.4.3, the rationale behind the design and development of the overall NSEM model is described.

2.4.2 SCI (Vt) Approach Toward Modeling of the Process of Navigation

The primary SCI (Vt) and USCG stated objective associated with modeling of the process(es) of navigation is to provide a procedure by which to quantify the effect of aids to navigation on vessel/mariner performance. In order to satisfy this objective, the modeling and analysis activities must extend beyond merely quantifying the effect of aids to navigation on the accuracy of information available; otherwise, vessel performance (i.e. safety) remains an unknown and would require predictive models quantifying this performance. Further, the problem cannot be partitioned, such as to consider the effect of aids on information accuracy, and subsequently the effect of information accuracy on performance. This is because the process by which the information is obtained affects workload, pilot/mariner action, and hence, performance. A Process of Navigation model, satisfying the objectives of this study, must appropriately consider the interrelationship between the information available, the information utilized, the mariner intentions, his control actions and the vessel dynamics.

Further, to be generally useful, the model results must also be of a statistical nature. In this way, the model can account for the effects of uncertainties (perception errors, variability between mariners and vessel characteristics, etc.) in the process of navigation. The model must also exhibit a deterministic character, in the sense that in a given situation the model will behave in a predictable (and therefore validatible) manner. Finally, the model must have a dynamic character, because the desired performance measures (safety, workload, convenience, etc.) are themselves related to the dynamic process of channel transit.

A key additional point, as mentioned previously, is that the model must be able to predict performance for conditions other than those for which the data was collected.

The SCI (Vt) approach satisfies these modeling requirements by:

(1) Deriving deterministic and statistical models for the dynamic elements of the process of navigation, drawing from the process of navigation interviews and data base, estimation and control theory and engineering practice;

(2) Incorporating a Monte Carlo feature so that statistically significant relationships can be established between aids to navigation and the accuracy of navigation;

(3) Allowing for inclusion of real or man-in-the-loop simulation data for model calibration or actual use (as in a table lookup).

The remainder of this subsection discusses the rationale behind the selection of the specific model form for each major element of the SCI (Vt) Process of Navigation model.

2.4.2.1 Dynamic Fast-Time Simulation

The SCI (Vt) approach emphasizes fast-time simulation (rather than man-in-the-loop real-time simulation) primarily because of the significant economic advantages. Under no circumstances can real-time experiments, of any form, be used to address <u>all statistically significant</u> results. Fast-time, predictive model capabilities are essential which can be validated conclusively using real-time simulation data and/or shipboard data.

Other advantages of full digital simulation exist, however, which have a tendency to offset the inability to "completely model the human." These advantages include the fact that the

"digital" experiments are fully controlled, from an experimental design point of view. Individual experiments are repeatable, permitting detailed situation analyses and accurate sensitivity studies. While the mariner model may not react like a human with 100 percent accuracy, it is always possible to determine exactly what it did and why; this is not only informative from a system evaluation point of view, but is also fundamental to model validation.

A fast-time digital simulation also lends itself well to calibration. For the most part, any information obtained from real-time experiments or any other data source can be suitably incorporated into a digital model. Most real-time experiments have operational deficiencies. Careful experimental design can be used to minimize the effect of the deficiencies and produce results and sensitivities that are totally valid. These can be incorporated into the SCI (Vt) model. In a sense, the model can be developed and calibrated by utilizing the results of other experiments and data sources without being encumbered by their respective deficiencies.

Lastly, fast-time digital simulation provides a baseline of results and a point of departure for specifying real-time simulation experiments. In this manner, a carefully selected subset of possible real-time experiments can be performed that are indicated as potential problems in the fast-time digital simulation as regards to operating scenario, aid configuration, etc.

Dynamic elements of the model include the vessel dynamics, as well as the mariner's thought processes and control actions, which vary with changing conditions during a channel transit. Non-linear effects (tracking tolerance threshold, etc.) point to simulation of some kind as the most tractable means of solving for the temporal relationship among these dynamic elements. A Monte-Carlo simulation technique was adopted, at least initially, in order to insure that the non-linearities and various mariner

decision options can be properly accounted for. A primary objective in deriving simulation models is to choose the simplest model which accurately depicts each necessary function. This approach facilitates validation and also maximizes model efficiency, making the final model feasible as a user-interactive tool. The dynamic elements of the navigation system evaluation model and the rationale for the selection of each are discussed below.

It should be understood that an integral input to the dynamic situation is the information from the aid configuration(s) chosen as the milieu in which the vessel and operator perform. Although the particular aid configuration is fixed to the extent that the mariner has no control over it, the information obtained varies as the vessel proceeds through the configuration as different navigational information becomes available.

2.4.2.2 Vessel Dynamic Modeling

Many possible forms exist for modeling vessel dynamics. These range from ad hoc geometry-based algebraic equations to highly sophisticated, six degree-of-freedom differential equations with hull shape effects included. The form selected for the vessel dynamics model lies between these extremes. It is characterized by:

(1) three degree-of-freedom motion (yaw, sway, surge), represented by three non-linear differential equations; and

(2) truncated Taylor series expansion of the hydrodynamic forcing functions, retaining only those terms which are of signficance in describing vessel motion in shallow waters.

This form was selected for the following reasons:

(1) It is computationally efficient

(2) It provides an accurate representation of the vessel's motion, particularly where pitching motions are minimal

2.4.2.3 Mariner Modeling

The mariner model selected and developed for the navigation system evaluation model is derived from human operator theory, and draws heavily from previous engineering models of the human performing estimation and tracking tasks, which have been successfully applied to aircraft/pilot, automobile/driver, and weapon system/operator system model. In concert with human operator modeling techniques, the mariner is divided into three basic functions:

(1) Estimation -- perceiving and predicting the vessel state;

(2) Decision -- determining what control strategies should be integrated at a particular time, if any, and

(3) Control -- determining and actuating control actions appropriate to strategic objectives.

Estimation. The estimator model represents those human functions embodied in perception and interpretation of the visual scene (environment) in order to extract visual "cues." Cues are those quantities referred to as "decision variables," those variables upon which the decision and control models can act. For Phase I, the estimator inputs have been restricted to visual parameters; Phase II will consider radar, effects of lighted buoys, etc., as discussed in Section 3.6.

In modeling the estimator function, strict isomorphism to humans is not assumed. That is, the estimation function need not exactly replicate the procedures (mental processing) by which the

mariner derives cues. It must, however, yield the same results which mariners achieve in a similar situation. That is to say, the input/output structure may be aggregated as long as the functional relationship of the observations to decision variables is accurately modeled.

The estimation model starts with a visual scene, which is geometry-dependent and changes during a transit. Various aids or combinations of aids are considered, and various coordinate rotations and translations are used to construct a table of "possible" aid groupings. The uncertainties associated with these specific configurations are also computed. As an example, angles between buoys are computed and rotated to equivalent along-track and cross-track errors. This function is second nature to the mariner and it is extremely difficult to verify the precise nature of such computations mentally performed.

The estimation function catalogs these results from various aids or groups of aids by listing them in decreasing order of importance (relative to the mariner). This ordering is performed by the associated uncertainty computed in the model. It is fair to say that the mariner chooses those aids or groups of aids associated with small uncertainties. Obviously, this characteristic is isomorphic to humans and as such represents a behavioral characteristic.

In a similar fashion, the mariner combines redundant measurements into one usable "equivalent" measurement with the same amount of information content. Again, this structure (the use of weighting functions proportional to covariances) is reasonable and has been verified to some degree in various human operator tasks.

The estimator model ultimately provides as output certain key decision variables, such as cross-track deviation, heading (rate), etc. It is important to note that experiments need not validate whether the mariner is cognizant of all of the steps he takes in

arriving at the decision variables, but rather whether the final results are consistent with those of the mathematical model.

Decision and Control. The modeling approach to the mariner's decision making and control application processes draws more heavily from prior research in human operator modeling technology. In particular, the approach to modeling of a mariner's course steering process parallels work done at Delft [6] where an engineering model of the helmsman of a supertanker was developed and validated by comparison to experimental data. The decision model postulates a mariner "preview" or prediction function, where he projects his track deviation and heading error some time into the future and applies control so as to compensate these projected conditions. Prior work has also suggested the presence of an "indifference threshold" in the decision logic, below which the human elects not to apply control [6, 11].

The control function has been found in prior work to exhibit precognitive characteristics [11, 13]. The approach to modeling control processes recognizes this factor by including a "learned" or preprogrammed catalog of control strategies (e.g. turn negotiation procedures) which are selected by the decision maker on the basis of the anticipated vessel state.

The decision and control models are characterized by a specific set of parameters, which have been selected so as to yield reasonable mariner response to selected situations. These characteristic parameters fall into the following categories: (a) threshold parameters (indifference thresholds, command quantum level), (b) preview or prediction parameters, (c) feedback gains, which determine command level.

The numerical values assigned to these parameters can be thought of as a consideration of prior knowledge about mariner response characteristics. In the same light, the parameters are capable of incorporating new data from validation experiments, thereby "calibrating" the model at the validation condition. This is an extremely valuable property of the model -- the model can thus be used to define and direct much of the validation experiments by indicating which parameters most heavily influence mariner performance, and consequently which experiments have the highest potential payoff. It is for this reason that SCI (Vt) has chosen to develop the overall model structure and then conduct experiments as opposed to first conducting experiments and then formulating the model.

2.4.2.4 Stochastic Features of the Model

As mentioned previously, a Monte Carlo simulation capability was considered desirable. This approach was selected for two reasons. First, a Monte Carlo simulation imposes no restrictions on the process being modeled. While assumptions and approximations may be made (linear error model, linear control gains, etc.), none of these is forced by the simulation technique. Thus, as the model development and validation activities continue, the option will exist to expand and modify individual logical elements without concern for the feasibility of doing so. The alternative to Monte Carlo simulation is covariance propagation. This latter technique provides a means to statistically propagate the effects of information available and its accuracy on performance, in a very expedient, efficient manner. However, as mentioned before, the elements being modeled must be constrained by linearity requirements. Incorporation of covariance propagation capability may be accomplished in Phase II, if the final model form lends itself to this technique.

The second reason for the adoption of Monte Carlo capability was in recognition of the fact that the final model results must be addressed in terms of statistics, and statistical significance. The model cannot properly consider the effect of aids to navigation on vessel performance based on only a single run or worst case analysis. It is appropriate to note, however, that Monte Carlo simulation can provide these latter results as well as multiple execution (repeated random sample) results.

2.4.3 Approach Towards Development of the Navigation System Evaluation Model

The Navigation System Evaluation Model has three primary purposes:

(1) To provide all user interface with the Process of Navigation model; including the construction/determination of all PON input parameters.

(2) To provide the model user with guidance and recommendations pertaining to aid configurations, vessel types, mariner requirements, and

(3) To save, in summary form, the primary process of navigation results of interest, to permit efficient user access to this information, as needed.

In summary, this model is an executive to the aids to navigation evaluation process. The SCI (Vt) objectives and approach regarding Navigation System Evaluation Model development stem primarily from the all-encompassing objective to provide the USCG with an efficient and usable model. Considerable effort will be devoted to ensuring its usability, discussed in detail in Sections 3.6.5 and 3.6.6.

In the initial portions of Phase II, the Navigation System Evaluation Model will serve primarily as the mechanism by which the Process of Navigation model can be exercised. As this effort progresses, the Process of Navigation model can be validated and numerous model results will become available. Other results will also be obtained from CAORF and other real-time experiments,

shipboard data collection, etc. As these results are synthesized by the SCI (Vt) project team, they will be incorporated into the Navigation System Evaluation Model, in the form of tables and empirical relationships. This model will then assume a results management role (per item (3) above). By the end of Phase II, Process of Navigation model execution will not be required, except when unusual or unique situations are being addressed.

In terms of form and structure, the Navigation System Evaluation Model is entirely different from the Process of Navigation Model. It is basically a data base management tool, with considerable emphasis placed on input/output convenience. This approach to the overall modeling activity permits the development of a Navigation System Evaluation model uniquely tailored to the USCG utilization requirements, without compromising the technical content, sophistication or even the required complexity of the embedded Process of Navigation model.

2.5 PHASE I MODEL UTILIZATION

The SCI (Vt) approach to the conduct of the Phase I effort encompassed the design, development and utilization of a Navigation System Evaluation/Process of Navigation model. Utilization of the model within Phase I was considered essential in order to demonstrate the viability of the overall SCI (Vt) Phase I/Phase II methodology. In particular, the Phase I model was exercised, and its results presented and analyzed, for the following reasons:

(1) To demonstrate the feasibility of the modeling effort, i.e. a digital simulation can in fact produce validatable, real-world results.

(2) To convey how the model results can be used to derive establishment/disestablishment criteria.

(3) To provide a tool (the Process of Navigation model) to assist in the identification of Phase II modeling and experiment requirements.

SCI (Vt) firmly believes that the Phase I effort must extend beyond a design activity, since even very thorough model design cannot ensure adequate model performance. On the other hand, the SCI (Vt) approach (for Phase I) does not encompass costly, man-in-the-loop experimentation. In light of the ability to use the Process of Navigation model for the identification of experiment requirements, and experiment design, the conduct of such experiments within Phase I was considered premature.

40X

40 blank

III. STUDY RESULTS

The objectives of the Aids to Navigation Systems Study, Phase I, are the definition of the elements of the process of navigation, and the demonstration of the feasibility of SCI (Vt)'s preliminary analytical model in the evaluation of the effectiveness of an aids to navigation system. SCI (Vt) is of the opinion that, not only have these objectives been met; they have been exceeded to the extent that direct application of results may be made in the initial stages of the Phase II study.

The Process of Navigation model is functioning and has been tested using a channel configuration similar to that of the Coast Guard Phase IIIB restricted water tests at CAORF. The characteristics of the 80,000 ton tanker simulated at CAORF were used in the SCI (Vt) dynamic simulation, employing a "digital mariner model." Although the trial runs encompassed a minimum number of situations, results indicate performance as would be anticipated in a real world situation, thus confirming the basic validity of the form of the inputs to the digital Process of Navigation model. There is no question regarding the need for refinement and tuning of these inputs before definitive results become available. But neither is there any question that a Process of Navigation model is not only feasible but is now functioning.

Section II has discussed the planned sequential approach to the model development. This section of the report describes the results of each step in sequence, the structure of the model, and the outputs of the trial model runs. The organization of this section is depicted in Figure 3.1.

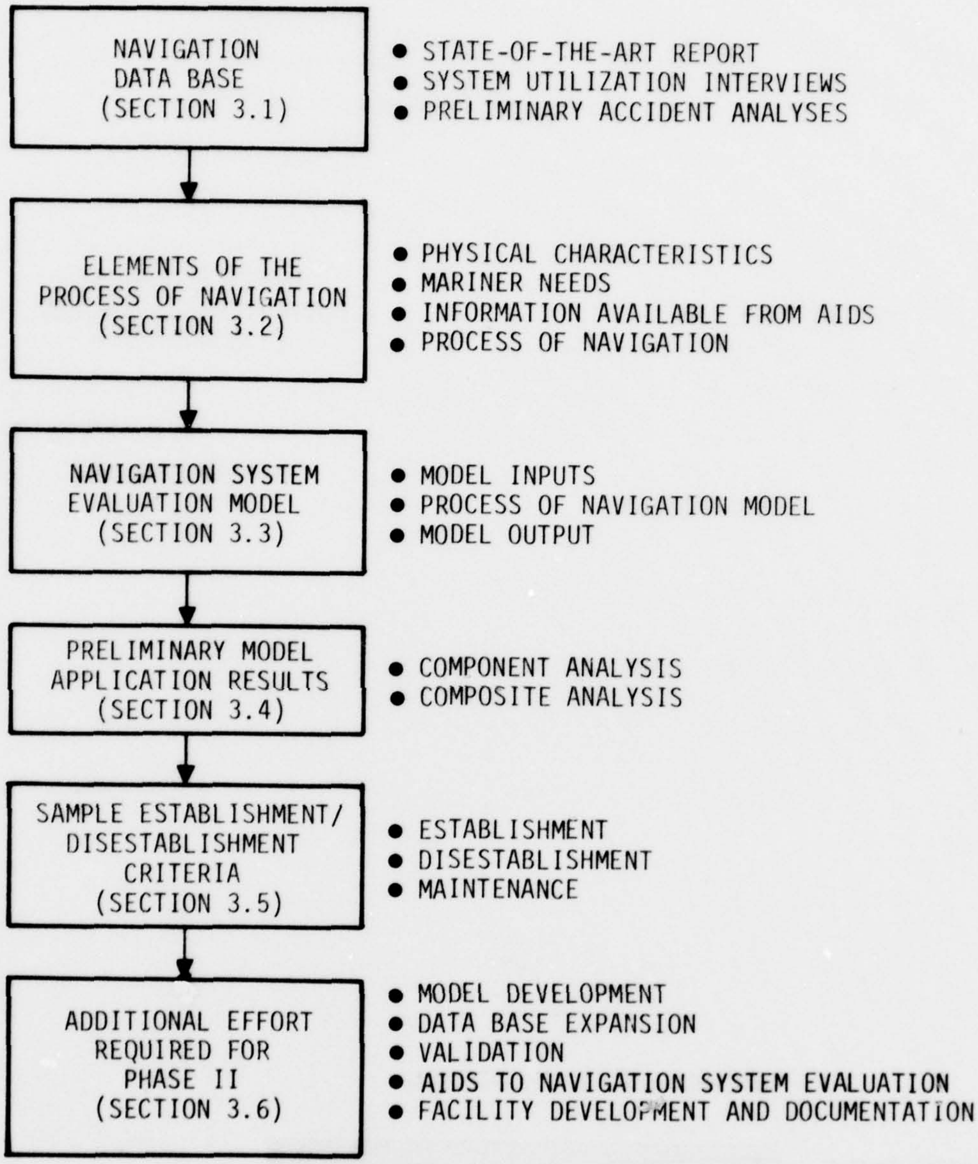


Figure 3.1 Organization of Section III

3.1 NAVIGATION DATA BASE

SCI (Vt) has developed and verified many models similar to the Process of Navigation model, and each of these was found to be highly dependent on different types of input parameters and data. Thus, prior to the initiation of model development efforts, a comprehensive data base had to be developed. This data base then led to qualitative descriptions of the elements of the navigation process. From these qualitative descriptions, quantitative relationships were defined and integrated into a coherent structure. The data base was not only sufficiently broad to encompass the immediate needs of Phase I, but also contains sufficient information for the initial Phase II requirements.

The first two months of the Phase I work efforts were devoted almost exclusively to the establishment of the data base. This included a preliminary examination of grounding accidents in selected ports, interviews with system users, researchers and planners, and a collection and analysis of prior studies which could impact the immediate and long-range objectives of the aids to navigation program. A review of facilities which could be utilized in Phase II as a means of model validation, data base expansion, etc. was also conducted.

The navigation data base is described in detail in Appendices A, B, C and D and is summarized in the following sections.

3.1.1 State-of-the-Art

The complete State-of-the-Art Report (Appendix A) presents and analyzes information in the following areas:

- Expert Interviews
- Aid to Navigation System Planning
- Research Facilities
- Literature Survey

The approach has been to examine representative samples of applicable work which has been or is being done, by whom, by what method, and where, and to assess the applicability of the efforts or facilities to the overall objective of the Coast Guard Aids to Navigation Study.

3.1.1.1 Expert Interviews

During the course of the study, interviews were conducted with 25 expert mariners both in the U.S. and abroad. The interview methodology is described in detail in Appendix A. The results of the interviews were used to identify the essential elements of the process of navigation, the mariner's needs for each navigational situation, and as an input to the determination of information available from aids.

3.1.1.2 System Planning Criteria

In order to review existing planning criteria, representative authorities were visited and, where available, written doctrine examined. Of those doctrines reviewed, the CG-222 series is the most definitive but, with the exception of a recommendation involving buoy spacing versus degree of environmental exposure (maximum 1 mile, minimum 1/2 mile), and the criterion that a mariner with a height of eye of five feet need only see two buoys ahead on each side of the channel (daytime) or two lighted aids ahead at night under average conditions, quantitative criteria do not appear.

Planning criteria for radio aids to navigation are in a relatively high state of definition and use compared to those for audio/visual systems. This is no doubt due to the fact that operational capability in terms of accuracy, reliability, etc., are readily available for a radio aid. The characteristics of receiving equipment can be described in detail; the mariner performing the same function for an audio/visual aid cannot be. The coverage and accuracy of a radio aid can and is completely described in

statistical terms. For example, the U.S. National Plan for Navigation establishes basic requirements for Loran-C coverage (0.25 NM, 95% of the time) in coastal confluence areas. The parameters of receiving equipment are in the process of standardization. In Europe, the installation of DECCA and the "Brown Box" at Rotterdam resulted from specific planning criteria. The studies for the ports of Antifer and Gravelines define planning criteria in the form of requirements for accuracy, based on traffic profile and available channel. These studies go so far as to define the minimum information to be presented to the navigator, the accuracies thereof, and even the units to be used.

We conclude that the state-of-the-art for radio navigation planning criteria is significantly more advanced than for audio/visual aids. We further conclude that the methods used to define requirements for specific harbor elements are directly applicable to planning for channels working with audio/visual aids, lacking only an equally definitive method of quantitatively defining the operational parameters (accuracy, coverage, reliability).

3.1.1.3 Research Facilities

The major potential of existing research facilities for contribution to the current study lies in the use of simulation, either radar simulators or large scale ship simulators, to conduct carefully structured experiments to determine and/or validate:

(1) The information used, in order of priority.

(2) The accuracy of mariner's perception of the information available.

(3) The information input to the decision process, and the decision process itself.

(4) The success or failure of the results of (1-3) above.

In the course of the current study, visits were made to a number of research facilities, the literature was surveyed for reports of others and some are familiar to the SCI (Vt) staff through

prior experience. The preponderance of research activity seems directed towards:

- Vessel Traffic Systems
- Collision Avoidance
- Vessel Dynamics
- Ship Handling
- Radio Navigation Applications.

Only recently has some work been accomplished on the psychology and techniques of channel keeping. Little of the work yields quantitative results to the extent of applicability to analytic modeling. Sub-experiments, usually psycho-visual in nature, have been accomplished to, for example, determine reaction to buoy lighting schemes, or determine the mariner's perception of angle or distance. The Coast Guard's restricted waterways experiments at CAORF (National Maritime Research Center, Kings Point) are the first "total type" experiments using large ship simulation.

Facilities applicable to future work toward the objectives of the Aids to Navigation Study fall into three categories:

- Training Establishments
- Academic/Research Establishments
- Operational Facilities.

Training Establishments

With the exception of Marine Safety International located at La Guardia Airport, New York, the facilities available at training establishments applicable to the current study involve radar simulation. Both collision avoidance and radar piloting may be accomplished with these facilities, often from multiple "conning" stations. The advantages of such facilities are two-fold:

(1) Reconfiguration of test presentations is relatively simple.

(2) A problem can be run simultaneously for as many as 10 subjects.

The disadvantage is the obvious one that only radar presentations are available. Nevertheless, a great deal of data on the use of radar in the process of navigation can be acquired readily through use of this type of facility.

The only non-government training establishment in the U.S. using large-scale ship simulations is Marine Safety International. The "scene" is a TV display of a scale harbor model observed through a camera. An advantage of this type display is the ease of changing aid configurations. Disadvantages include large angular distortions beyond about 30° from the bow, and the difficulty of introducing other traffic into the simulation.

Academic/Research Establishments

Of those institutions and organizations surveyed under this category, the primary U.S. facility, generally applicable to any facet of exploration into matters under study, is the Computer Aided Operations Research Facility (CAORF), located at the National Maritime Research Center, Kings Point, New York. CAORF provides ship simulation with computer generated visual displays and has the capability of being programmed for any combination and characteristic of aid to navigation or other vessels. Experiments are currently underway on the "human factor" in the navigation process.

The advantages of CAORF are the simulation capability, research staff and their on-going experience in aids to navigation. Disadvantages include lack of parallax, size and light intensity of aids and the costs of lengthy experiments.

Operational Facilities

There are only a few operational facilities in the U.S. which can provide an input to the parameters of this study. One such facility would be the VTS at San Francisco, where the high resolution radar could be used to collect vessel position and maneuvering

information. Unfortunately, there are relatively few NAVAID configurations within its radar coverage, severely limiting its utility.

Data from facilities in Europe may prove highly valuable in the design of aid systems for deep water ports such as LOOP. There may be a direct relationship between the experiments now being conducted at several European ports and the requirements analysis for U.S. ports.

3.1.1.4 Literature Survey

The bibliography developed by the Coast Guard combined with additional source material provided by the SCI (Vt) marine librarian show an extensive literature inventory addressing the subject of marine navigation. For convenience, the subject areas were subdivided as follows:

- System Planning and Evaluation
- Element Design (Hardware)
- Vessel Dynamics
- Human Factors
- Collision Avoidance/Traffic Analyses

Published material was surveyed and representative documentation examined in detail in search of method and applicability, defined as the SCI (Vt) approach to the state-of-the-art analysis. The results are summarized below.

System Planning and Evaluation

Examples of sophisticated study efforts directed toward the definition of requirements and forms of solution were found almost exclusively to involve new and unique installations such as the VLCC ports at Gravelines and Antifer. Methods used to define information required and accuracy thereof of necessity involved a significant degree of vessel dynamics in the restricted water environment and, in those ports studied, invariably resulted in the recommendation for some form of radio aid. Visual aids were

considered insufficiently accurate for a system intended for operation under all conditions.

Our conclusion resulting from bibliography and literature search is that a methodology is not generally available, in the audio/visual area, for quantitative planning and design of aid configurations within the context of the objectives of the current study.

Component Design

Research into the design of components making up an aid to navigation configuration (with the exception of radio aids) seems largely directed to the area of optics. Examination into range of visibility of lights and shapes, as a function of physical design and meteorological conditions, has been accomplished in some detail. Little seems to have been done to develop relationships among different configurations of aid components. Interestingly enough, we can find little evidence that any significant reconfiguration of aids has ever taken place based on improved characteristics of the individual components making up the configuration.

Vessel Dynamics

Theoretical and experimental data regarding vessel dynamics seems to be at a relatively high level, although actual experimentation, at sea, is continuing. The major pre-occupation is with very large ships both as to general tactical characteristics (turning radius, advance, transfer, stopping distance) and with behavior in restricted channels under the impact of bank and bottom effects. We conclude that, within the objectives of the current Coast Guard study, based on information presently published, sufficient analytical capability for vessel coefficient definition exists in the form needed as an input to the process of navigation model. Insufficient data exists concerning specific coefficients on older, less maneuverable vessels, and very little sea trial

data exists for the number of operating conditions which are necessary for simulation.

Human Factors

The literature reveals some human factors experiments, primarily involved in stress due to workload and uncertainty. Psychovisual experiments are reported which examine, for example, light color preference, workload, etc. One ambitious experiment involved an attempt to examine the decision making process under actual operating conditions by audio (and in some cases video) recording, in narrative form, the commands and rationale of pilots conning vessels through selected harbor elements. Some work addressing duties and analysis of crew skills has been reported but the information does not lend itself generally to definition of the process of navigation.

Previous work involving human modeling and its applicability to the modeling of a mariner is discussed in Appendix E.

Collision Avoidance/Traffic Analysis

A large segment of available literature deals with the problems of crowded waters and methods whereby traffic may safely be routed through them. This is a matter of great concern in the world's major harbor and high traffic density areas. From the point of view of the objectives of the current Coast Guard study, little of this information is directly applicable. Aids to Navigation are primarily anti-stranding systems and, with the exception of certain traffic control installations which <u>secondarily</u> may provide navigation position information, are not directed toward the collision avoidance problem.

3.1.1.5 State-of-the-Art Conclusions

The primary conclusion concerning the state-of-the-art of the audio visual aids to navigation system is that methods for quantitative analysis of <u>integrated</u> aid to navigation systems, or

quantifiable parameters defining the process of navigation adequate to support such an analysis are not significantly represented by the current state-of-the-art. The state-of-the-art does, however, reveal some examples of methodology and analysis results applied on a micro-scale to specific ports, specific vessel types, and specific channel configurations which provide some application as baselines from which to proceed. These include:

(1) Statistical application of the parameters "effectiveness," "adequacy," and "utilization"as appearing in the work of EASAMS Ltd. [1].

(2) Methods used to define both operational and user capabilities in analyses of radio aids to navigation as potentially applicable to visual aid configurations.

(3) The recent application of large scale ship simulation in collecting data on decision making as a function of information provided.

(4) The capability of fast time simulation on digital computers permitting statistical analysis of processes heretofore capable only of real time simulation and observation.

Finally, based on discussions and interviews with interested parties, we find a general satisfaction with the audio/visual system as implemented, albeit that implementation has evolved through the application of experienced judgement as opposed to resulting from the imposition of rigid, quantitative planning criteria.

3.1.2 Accident Analysis

A small sample of commercial vessel casualties was examined to determine whether or not aids to navigation could be considered as being related to the casualty. The relationship was not specifically oriented towards any concept that an aid causes the incident to occur, e.g., a vessel grounded due to a buoy being off station or a beacon extinguished. The data review was primarily oriented toward the mariner, and his ability to judge or misjudge a situation where aids were used for navigation. The results of the casualty data

examination would hopefully reveal patterns of where accidents occurred, whether the mariner misjudged vessel location using aids, or whether other misjudgements contributed to the casualty. The complete data and analysis is presented in Appendix D.

3.1.2.1 Data Selection

A computer printout of the USCG Commercial Vessel Casualty tapes was obtained. The selection was based upon the following selection criteria:

(1) Vessel groundings only

(2) Areas of New York, Delaware Bay, Chesapeake Bay, and Texas

(3) Vessels were over 300 gross tons and excluded equipment or structural failures

(4) Data from 1971 to 1976.

Three hundred fourteen (314) cases were obtained in the printout. Manual screening to encompass only mariner judgement reduced the number from 314 to 137. A further screening to eliminate cases such as anchors dragging, barges adrift, etc. reduced these to a final number of 83.

3.1.2.2 Analysis Results

The number of groundings categorized by harbor module is shown below:

MODULE	QUANTITY
Bend	41
Straight	25
Entrance	10
Anchorage	5
Other	2
Total	83

Notably, bends account for nearly 50% of the listed groundings. The accidents were further categorized by environmental conditions:

	QUANTITY
Visibility: Fog, Rain	5
Visibility: Clear	36
Time: Day	20
Night	19
Twilight	2
Traffic	1
No Traffic	40
Wind, No Current	24
No wind, minor current	17
Aids mentioned	5
Aids not mentioned	36

In terms of vessel age, the number of cases by five-year groupings (age at date of accident) is

	AGE					
	0-5	5-10	10-15	15-20	20-25	25-30
Straight ...	5	6	3	5	3	3
Bend	12	4	4	7	7	7
Other	5	2	3	1	3	3
Total	22	12	10	13	13	13

Vessel length in relationship to the number of casualties is described below:

Length	>700	6-700	5-600	>500
Number	19	30	20	14

3.1.2.3 Accident Data Conclusions

Although the sample size of reviewed accidents was rather small, several conclusions can be reached which will influence the modeling efforts, particularly in Phase II. The conclusions include:

(1) Navigation at bends is a primary area of concern. There is a need to examine the methods employed in the aid to navigation system to ascertain if there is sufficient information available to the mariner enabling him to properly judge the movement of the vessel. "Too wide a turn" is a term which frequently appears in the casualty case review.

(2) The differences in day versus night are not highly significant. This supports the statements by most mariners that unlighted aids in major shipping channels may be a hazard or at least not contributory to navigation safety.

(3) Vessel maneuverability is a significant factor in that many present research facilities have not programmed the characteristics of vessels which may be less maneuverable. Maneuverability and size may be interactive, i.e., a large maneuverable vessel may have the similar process of navigation problems as a smaller, but less maneuverable vessel.

(4) Although anchorages do not appear relatively high on the incidence list, their lower frequency of use versus incident may have some significance. This might indicate a need for better markings of anchorage limits.

(5) The incident rate for junctions is negligible in this limited analysis. Thus, despite the requirement for increased caution and collision avoidance maneuvering, aids to navigation do not appear as a significant element at junctions.

(6) The misidentification of aids at entrances can be directly related to an experience factor. All cases occurred where no pilot was on board. This may indicate a need for better differentiation of entrance aids, since all of the cases involved entrances from sea rather than a channel entrance once inside a bay or harbor, or a departure from the harbor to the sea.

3.1.3 Specific Port Comments

During the course of interviewing experts in the process of navigation, mariners pointed out that certain aids may not be of significant value in navigating deep draft channels. This information was derived either through the mariner's omission of an aid in describing a harbor transit, or as a result of specific questions concerning the aid. They also commented on the need to add aids for increased safety, or change such characteristics as light intensity, since it did influence their ability to navigate under certain conditions. Appendix B describes these comments for several ports in the northeast corridor.

The specific port comments might appear to be only relevant to that port. However, they do contribute to the overall scope of the study, in the following manner:

(1) By pointing out aids which are not used, they helped define a priority in selecting information available from other aids and outside sources. This was relevant to the design of the model which has multiple aid sources available, e.g., developing the methodology which assigns a priority to selecting the information which has the highest utility.

(2) Additional desired aids provide the opportunity of modeling configurations which would confirm or deny mariners opinions stated in a desire to improve safety or facilitate movements.

(3) These comments represent one of the few occasions in which mariners have indicated a willingness to give up or swap aids. The key to obtaining this information appeared to center about swapping aids to increase their utility, and eliminating aids which might be hazardous.

(4) Specific comments substantiate many of the general conclusions developed in the question and answer portion of the mariner expert interviews, such as those regarding unlighted aids.

(5) The comments on RACONS versus Radiobeacons on approach aids is one of the few firm comments received concerning electronic navigation. This comment stated that RACONS were preferred over Radiobeacons on large buoys which defined a sea lane approach to Delaware Bay because

RACONS are directly observable on radar, which is constantly in use during the approach, and that RACONS appeared more reliable than Radiobeacons.

Although the specific port comments were helpful in establishing the data base in Phase I, they will also be highly useful in Phase II. SCI (Vt) recognizes that these comments were obtained from a small group of mariners within a large population, but we believe that conversations of this type reveal a large amount of information which lead to system improvement.

3.2 ELEMENTS OF THE PROCESS OF NAVIGATION

This section describes in detail the structure of the Process of Navigation Model. As a basis for the development of this structure, certain elements of the process were examined and defined to the extent necessary to ensure the validity of the model design.

The process of navigating a vessel into or out of a harbor involves a decision making process to which the following elements all make a contribution:

(1) *A priori* information and learned behavior.
(2) Physical characteristics (of the harbor, vessel, etc.).
(3) Information available from aids.
(4) Accuracy requirements.

Previous sections of this report describe the methods of collection of data relating to certain of these elements. The first three elements involve inputs to the Process of Navigation Model. Accuracy requirements are used in the overall system evaluation process as a basis for comparative analysis. The following is a discussion of each of these elements of the process of navigation.

3.2.1 A Priori Information and Learned Behavior

Prior to entry or departure from the harbor, a mariner has an inventory of information available to him derived by previous personal observation, or conditioned by past experience in the form of learned behavior. In addition, he frequently updates this inventory as a transit is in progress.

The interview subjects experienced difficulty in explaining situations which involve judgements and actions derived from learned behavior. This was evidenced by the inability of most mariners to quantitatively express a condition or action which was accomplished in an automatic thought process.

3.2.1.1 A Priori Information

The process of navigation is influenced by information obtained or derived prior to commencement of a transit, and by changes in information during the transit. Listed below are examples of the types of such information:

(1) Tide. The state of the tide determines the ability of certain deeply laden vessels to complete the transit without grounding within the channel limits. The tidal status is ascertained from a mental adjustment from the previous day in the case of pilots who are on a double voyage, consultation with other pilots or mariners based on extraordinary conditions of prolonged winds reducing the water levels, and checking tide tables.

(2) Docking or undocking time. The company or pilot dispatcher relays this information to the mariner. It can be influenced by dock workers overtime schedule.

(3) Visibility. The state of visibility along the route is determined from monitoring radio traffic. The mariner makes his own assessment of the visibility by observing an aid, other vessel, or bow or stern of own vessel.

(4) Anticipated traffic. Security calls, checks with pilots, etc. are made to determine the anticipated traffic enroute.

(5) Anchorages. Specific designated anchorages in major harbors require advance authorization to anchor and notification of departure. This authorization is obtained from the Coast Guard.

(6) Local procedures. Certain harbors have instituted local procedures to enhance safety. Passings may be restricted at certain bends, or may be desired at specific bends due to the increased width. Overtakings may be precluded in areas where the transits are short, and no appreciable time would be saved.

(7) Exclusive transits. Certain vessels such as LNG carriers may be given an exclusive escorted passage.

(8) Intended channels. Mariner's plans for passage through a particular channel infer knowledge of the general location of crossings, junctions, bends, etc.

(9) Aid discrepancies. Notices to Mariners, radio messages, and notes on the pilot dispatch bulletin boards provide information on aids missing, off station, or with light outages. Prior to entering different harbor modules, mariners check the location of aids, either visually, by radar, with respect to other nearby aids, or shore sources.

(10) Current. Experienced pilots are aware of current conditions existing at critical points in the passage based primarily on the past experience correlated with the tidal state.

3.2.1.2 Learned Behavior

Learned behavior has a significant impact on the ability of a mariner to navigate safely. It encompasses the collection of information cited in 3.2.1.1 above, and also includes items such as:

(1) turn rate judgements
(2) discrimination between angular observations
(3) sensing bank suction
(4) estimating distances.

Such learned behavior impacts the process by which the mariner processes information in estimating the vessel state, as will be discussed more fully in Section 3.3.

3.2.2 Constant Parameters

The physical characteristics which are used in the model are described, along with rationale which may limit their utility in Phase I. These physical characteristics are those over which the mariner has no immediate control, i.e. the vessel design, aid placement, environment, etc. He will have operational control of the vessel, but the effect of his actions are dependent upon vessel maneuvering characteristics.

3.2.2.1 Harbor Modules

As defined in the Coast Guard furnished glossary, a harbor module has a certain physical shape which can be generically described, readily visualized, and located on a chart. Initially, SCI (Vt) described a large number of harbor module terms which included: straight channel, bend, truncated bends, crossings, junctions, anchorage obstructions, etc. However, as the actions of the mariner were examined and compared with the model decision and control elements for a crossing, a junction or a bend became the same, if the mariner plans to maintain a specific track. In the interview process, at no time did any mariner indicate that he did not have a specific intention prior to arriving at a harbor module transition. The only comment made was that the aid system should have a nighttime message content identifying the harbor module transition. Daytime transitions were evident from the general placement of the aids.

By combining redundant modules, SCI (Vt) reduced these modules to:

(1) straight channel
(2) bend
(3) entrance or restriction
(4) obstruction, either fixed or moving.

In defining these modules, there are overlap areas which are a quasi no-man's land, the exact description varying with the situation. However, the SCI (Vt) model does not require consideration of separate modules so that the vessel transit is a continuous process through the harbor of interest.

3.2.2.2 Vessel Characteristics

Maneuvering characteristics of a vessel inherently affect the ability of a vessel to transit a harbor module. The most significant of these include length, beam, draft, height of the vessel's bridge, turning radius and stopping distances.

The vessel hydrodynamic equations will have a direct impact on the SCI (Vt) model. However, these output variations are the same as would occur on a research facility simulator, such as CAORF, which might be used to validate certain parameters of the SCI (Vt) model. As an example, both the SCI (Vt) and the CAORF simulations can use the 80,000 DWT tanker. Mariners at CAORF have indicated that "things just do not feel right" for certain situations. To determine a possible adjustment to the feel of maneuvering, SCI (Vt) is developing maneuvering equation sensitivity parameters under a separate contract to MARAD. These parameters will be applied to the simulation computer at CAORF, and a sufficient number of runs conducted until the mariner feels comfortable.

Several vessel maneuvering conditions were not considered in Phase I, including bank suction, bow cushion effect, and squat. Squat is known to reduce ships speed, but the exact values are not presently known. Present testing of several large vessels in shallow water may give results which could be included in Phase II.

Measurement devices on board the vessel also influence the process of navigation. The instruments most frequently used include a compass, rudder indicator, speed log, and radar. Depth reading devices may find use in specific situations. Radio navigation equipment such as Loran, Radiobeacons, etc., are infrequently used

within the harbor. RACONS are used where available because they present a display on the ships radar. These are preferred by many mariners since they provide a clear identification of the aid, and because a separate item of hardware is not required to make the observation and measurement.

3.2.2.3 Charts and Aids

For purposes of Phase I modeling, navigational charts, i.e., specified geographical references are omitted. The pilot, in order to be licensed, must have his local area chart memorized. However, Phase I modeling is based on the relative position of aids to navigation in the defined harbor module and the geographic reference has no significance.

Aids to navigation, of course, are vital to Process of Navigation modeling and must be defined with respect to location within the module as well as with respect to their information content. Section 3.2.3 briefly addresses the question of information availability, a subject covered in detail in Appendix C.

The placement of buoys in the Phase I model assumes fixed location (i.e., no watch circle) at the extreme edge of the marked harbor element. Phase I permits the use of lighted or unlighted aids. All aids are considered to be detectable at the limits of their theoretical visibility for the situation selected. For example, an unlighted aid whose clear daylight visibility is 3.8 miles is considered by the model to be visible at 3.8 miles during the day (unless restricted by meteorologic visibility), but is considered invisible at night.

3.2.2.4 Situation Modifiers

The final physical elements in the process of navigation are the environmental effects on the vessel. These include the presence of other vessels, which constitute both a restriction in available water and act as a moving aid to navigation; current, which can

create a difference in desired versus required heading (and/or speed over the ground); and wind, which may have the same effect as current, albeit in a different direction or velocity. Visibility is an environmental effect which tends to change the mariners process of navigation in a fashion similar to the transition from day and night.

During Phase I, current was implemented in the model, and included the effect of variability along the track. Wind and traffic were not included.

3.2.3 Information Required and Available from Aids

3.2.3.1 Parameter Development

Appendix C discusses the information available from aid to navigation configurations in considerable detail although, because of space limitations, the appendix itself is a summary of the extensive detailed approach taken in the development of the Process of Navigation Model. The value of the PON model lies in its ability to reproduce and carry out defined operating procedures based on this information. The Navigation System Evaluation Model, of which the PON is a part, can then compare the results of the defined maneuvers which are, in turn, based on the information content of the aid configuration under test. The result represents the success, or failure, of the configuration to meet the requirements of the defined harbor module. The PON model, of course, takes into account all the maneuvering variables discussed in preceding sections as it simulates the navigation of the defined vessel through the module.

The basic approach taken to the development of parameters suitable for modeling involved the identification of measureable or "perceptible" information in the form of distances, distance differences, angles, and angle differences. A perception of the

relative values of any or all of these parameters, depending upon the basic aid configuration, was then translated into information necessary to maintain the defined track line within the specified harbor module. Specifically, the model is capable of producing the following information based on the defined parameters perceived:

(1) Cross-Track Position
(2) Along-Track Position
(3) Cross-Track Velocity
(4) Along-Track Velocity
(5) Heading Change Rate
(6) Distance
(7) Course to steer to correct perceived position and/or track errors.

The various configurations of Appendix C will obviously yield different results. The PON model reflects the quality of the information content from a particular configuration and hence is capable of determining the success or failure of the transit through the specified harbor module.

3.2.3.2 Priority of Information

In many aid configurations presently in existence, there is more information available to the mariner than that which is minimally required for safe navigation under normal conditions. Because of this excess information, the mariner mentally assigns priorities in selecting which aids he will use to develop the position and guidance criteria within the process of navigation.

The selection of information to be processed by the mariner is dependent upon the situation, primarily the vessel's location with respect to the aids, and the attitude of the vessel with respect to the channel configuration. The utilization of information will be considered in the next section of this report. However, the two additional items concerning the information available will be presented since they have a significant effect on the modeling accomplished in Phase I.

The first item concerns the results of interviews where mariners opined that certain information available was not used in the direct process of navigation. The opinions related specifically to deep draft vessels within and approaching the harbor. Areas of insufficient information were also identified:

(1) Lateral day color significances and lateral shape significance. Mariners stated that if they were able to see the aid along with other aids, the lateral significance was inherently defined.

(2) Light characteristics, i.e. 2-1/2 versus 4 second flash, was not used to discriminate between aids when the channels had short aid spacing. For large aid spacing, there were more frequent expressions of desire to retain the different flash characteristics.

(3) Junction day markings were not needed, but night markings were.

(4) Numbers on aids were considered a convenience. Although they could not be seen at night the numbers are used as a location identifier in security calls and arranging for passings.

(5) Sound signals from aids are not used.

(6) Long-range lights in harbors are not used as all-around aids. They are used if a part of a leading line range or as a single-point steering guide.

(7) Aids astern are not frequently used, unless there is a lack of information available from aids ahead.

(8) Unlighted aids provide no information at night in main shipping channels and are considered a hazard, or at least a nuisance, unless they are radar conspicuous.

(9) Several key entrance aids are not adequately identifiable when in areas where many vessels or boats anchor nearby.

The second item covers areas where mariners had a preference for use of information when more than one type of information was available, or, if within a certain harbor, there were several different aid configurations in different channels. There is no priority to be assigned, since these items are again situation dependent. The preference items include:

(1) Lighted versus unlighted aids.

(2) Leading-line ranges, particularly in channels not heavily marked with other aids, and waterways which have short reaches.

(3) Turning aids on the inside of turns (USA) versus own side of turns (European)

(4) Gated pairs, where water depths are bounded by the channel definition

(5) Changes in angular aspects of aids ahead give more timely information regarding cross-track error than a distance estimate to the channel boundary

(6) Entrance buoys at least one mile from a channel entrance are required for large vessel alignment with the channel despite the availability of a well marked channel

(7) In turns, mariners will use the aid which has the finest angle on the bow for turn rate information, if the aid is at a reasonable distance from the vessel.

3.2.4 Navigation Accuracy

In order to achieve a successful transit of a harbor or harbor module, there are certain limits of vessel position and attitude which cannot be exceeded without grounding. There are two methods by which these limits can be expressed: theoretical, based upon the vessel characteristics and the channel boundaries; and those which are perceived by the mariner. In a strict sense, they are not an element of the Process of Navigation. However, they do place bounds on the navigation process.

3.2.4.1 Theoretical Bounds

A simple description of a theoretical bound is shown in Figure 3.2. With a velocity Vt_d dictated by initial ship speed, conditioned by the drag effect of rudder angle, a mariner delay of 10 seconds, a vessel at an angle of H_E from desired track will go aground at a point where the turning radius R becomes tangent to

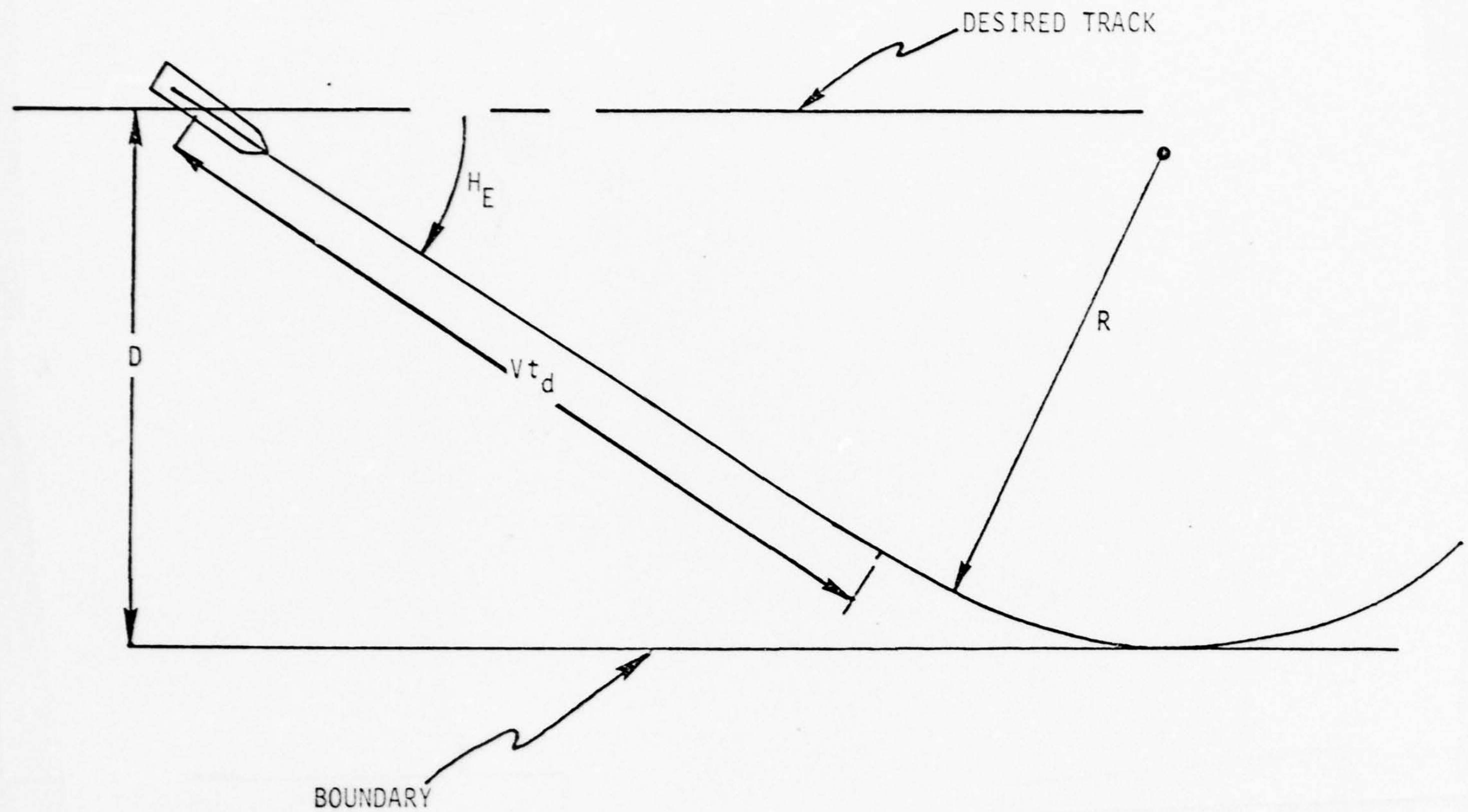


Figure 3.2 Theoretical Bounds, Straight Channel

the channel boundary. A complete series of curves for various vessels, heading angles, delay times, etc. would yield a library of boundary limits for a straight channel configuration. Similar boundary values can be determined for the various harbor modules under evaluation. From these boundary limits can be derived the limits of vessel states, i.e., along track position, along track rate, cross track position, rate, etc. Using worst case conditions and probabilities of occurrence, system requirements can be developed.

A good example of the latter is the derivation of the electronic system requirements in the approaches to the Port of Gravelines, accomplished by EASAMS Limited [2]. In this example, specific limits were placed on the data inputs, which included VLCC maneuvering characteristics, current variations, and assumptions of certain mariner estimations. From this data was derived the electronic system requirements, including readouts to the pilot or mariner, to transit several sections of straight channels. The readouts are vessel states of cross track, along track, etc., which is the same type of information presented in the SCI (Vt) model. Unfortunately, the analysis did not include the requirements to transit the bend joining the two straight channels.

When the Monte Carlo processing of the SCI (Vt) model is completed for a particular situation, the limits of accuracy or accuracy bounds will be contained in the results of the trials. These can be used to define the worst case conditions, shown when a particular harbor module becomes particularly dangerous, and also can assist in defining general system requirements.

In our original concept of considering theoretical requirements or bounds, SCI (Vt) had hoped to define these parameters without requiring consideration of anything but the vessel size and channel limitations. The analysis, however, indicates that the vessel attitude with respect to the channel is a critical item. The vessel attitude in turn is dependent upon the mariner. Thus the theoretical limits can only be derived if the mariner has a limit on the angle of the vessel, or a perceived requirement. This mariner limit can

be obtained through interviews or experimentation. In several interviews, mariners were asked what would be the crab angle they would not want to exceed in a specific channel. Several expressed a value of 10° for an 800 foot wide channel, others could not quantify their answer. There were insufficient mariners questioned to place any statistical significance on the answers received. This effort will require expansion in Phase II.

3.2.4.2 Perceived Requirements

Each mariner has an acquired set of values which he establishes as limits to vessel location or motion. This learned behavior pattern may be unique to a vessel which has a licensed master, or common to a group of vessels for a port pilot. In the interviews with mariners, SCI (Vt) attempted to obtain qualitative and quantitative expressions of these values so that they could be utilized in the Process of Navigation model. Other references were also reviewed to ascertain if these values had been expressed for other programs, such as the design of ports and dredging requirements.

Table 3.1 lists those questions or situations where quantifiable answers were obtained, and the estimated percentage of mariners giving the same answer.

3.2.5 <u>The Process of Navigation</u>

The process of navigation in restricted waterways is directly related to the information available from aids to navigation. The navigation process then deals with the overall selection of a route which involves a series of guidance and control strategies (tasks). The mariner's process of navigation consists of a hierarchy of navigation, guidance, and control phases conducted simultaneously with visual search, recognition, and monitoring operations. The mariner is the operative element in the process; he adapts and manipulates his dynamic characteristics to satisfy the key guidance and control requirements for the mariner/vessel closed-loop system.

Table 3.1

Requirements

NO.	QUESTION OR SITUATION	ANSWER	%
1	Does the present system of aids to navigation satisfy your requirements for safe transit?	Yes, except for small suggested changes and after major storms or ice periods.	100
2	Does zero visibility stop traffic?	No, for areas other than New York. Yes, for the Sandy Hook and Kill Van Kull areas in New York	100 90
3A	At a harbor entrance, how far from the channel is vessel alignment with the channel desired?	3/4 to 1-1/2 miles	75
3B	Minimum distance?	3/4 miles	60
4A	If a fairway buoy is placed at an entrance, how far should it be from the entrance?	1-1/2 to 2 miles for 800 feet and less	80
4B	Minimum?	1 mile	60
5A	At what distance from a straight channel boundary do you become uncomfortable?	50 feet if the current is from that boundary	75
5B	VLCC's	2-3 beams	75
6	Where should floating aids be placed at a channel?	At limit of dredged channel	100
7A	Is there a requirement for special aid identification at a junction?	Yes, at night	100
7B	Bifurcation?	Did not know the meaning of bifurcation.	100
8	How much of an error can be tolerated in along track position before a turn might be missed?	About 1 shiplength for large vessels, depending on bend angle	15
9A	In a straight channel head to head meeting situation, how far apart are the vessels before the break is made?	3-4 shiplengths (European) 2-3 shiplengths (USA)	85
9B	Minimum?	2 shiplengths	
10	At what distance do you prepare for a turn?	3-4 shiplengths	85
11	How much allowance is given for ship advance at a turn?	2/3 to 1 shiplength, depending upon angle of bend and whether turn is inside or outside	70
12	Which aids are used for turn commencement in a narrow channel?	Inside - USA Own side - European	80 -

There are three general levels of control behavior of the mariner in the process of navigation. These levels are precognitive (a learned maneuver executed in an open-loop way); pursuit (relying on preview information upon which the mariner takes advantage of a knowledge of the system input to structure a control strategy) and compensatory (or regulation, which implies an operation on a perceived error between actual motion and desired motion).

3.3 NAVIGATION SYSTEM EVALUATION MODEL

The navigation system evaluation model (NSEM) is the central element of the overall SCI (Vt) approach to the evaluation of aids-to-navigation. This approach consists of the use of established USCG guidelines and perceived mariner requirements, in conjunction with validated computer programs, in order to arrive at decisions regarding aids to navigation needs. A systems approach was followed in developing this procedure. The following sections outline the overall NSEM model and its key element--the process of navigation (PON) model.

3.3.1 Overview

The concept of the NSEM is depicted by the block diagram shown in Figure 3.3. As indicated, there are two main NSEM processing elements. In the first element (NSEM(I)), the user inputs the scenario of interest. This consists of: (1) the waterway geometry (harbor module description), (2) vessel characteristics, (3) the environmental conditions (modifiers - such as current, wind, etc.) that will affect the navigation task, and (4) the candidate aids to navigation to be evaluated. The NSEM(I) processing will then determine several quantities that must be taken into account for further analysis. These include:

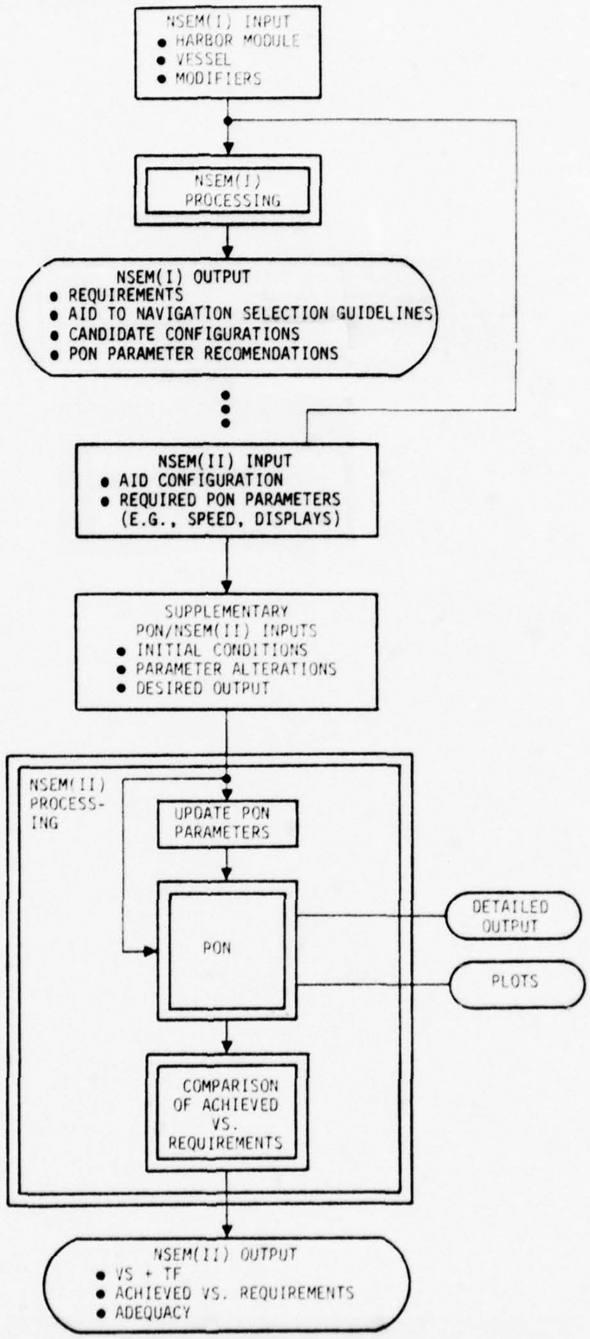


Figure 3.3 Block Diagram of the Navigation System Evaluation Model

(1) Basic requirements that must be considered for this particular harbor module. This includes items such as: (a) the need to provide safe passing regions to account for normal traffic movement, (b) the need for lighted buoys, and (c) periods of time the harbor cannot be navigated because of strong current or insufficient depth for a given vessel.

(2) Guidelines that have been previously developed for selecting aid to navigation configurations for a channel(s) such as those being considered. These guidelines address the channel as divided into segments (or modules) and the basic navigation requirements for each.

(3) Candidate aid to navigation configurations for the given harbor based on the requirements and guidelines given in (1) and (2). These configurations include both arrangements of a given aid type, alternate types (buoys, ranges), and the utility of possible radio aids (Loran, Omega, GPS).

(4) Recommendations concerning how the user should proceed to use the above information in proceeding to use NSEM(II). For example, obvious priorities may be given on the aid configurations for the given area. The PON model that is used as part of NSEM(II) needs specific inputs, and these will also be defined.

For the most part, the NSEM(I) model will not "determine" or "derive" this information; rather, it will be prestored in the form of text, tables, equations and algorithms. The data, or knowledge, to support this portion of the model will be based upon previous model results, sensitivity studies, mariner opinion, SCI (Vt) experience and published reports. Wherever practical and valid, previous model results will be summarized and generalized in the form of algorithms, designed to prescribe requirements and/or guidelines, and incorporated into the model.

The primary purpose of the NSEM(I) processing is to guide the user through a sequence of input/decision steps and trade-offs he should consider. This process is amenable to computer graphics technology as discussed in Section 3.6.5.

When the output of NSEM(I) is available, the user inspects it to decide what aid to navigation configurations he may want to examine more closely. Essentially, NSEM(I) presents him with

several options from which he may choose, based on his own experience and judgment. The user then proceeds with NSEM(II).

The purpose of NSEM(II) is to evaluate specific aid to navigation configurations in detail. This evaluation consists primarily of repeated simulation of the navigation process utilizing the process of navigation (PON) model (summarized in Section 3.3.3). From this simulation, performance measures are obtained which allow the user to assess the adequacy of the current system of aids to navigation in a particular area, and what future action to take. This includes information related to vessel safety and traffic facilitation (VS+TF). The outputs of NSEM(II) are discussed further in Section 3.3.4.

The inputs to NSEM(II) are the parameters which guide the PON model, the variables which control the information to be computed, and desired values for comparison with the model outputs. NSEM(II) exercises the PON model in various ways (sensitivity runs, worst case runs, Monte Carlo runs) to obtain various performance measures. These performance measures are then compared with desired/required values to allow the user to assess the adequacy of the specific aid configuration under evaluation.

The following sections describe the NSEM inputs, a summary of the PON model, and the NSEM outputs.

3.3.2 Model Inputs

The purpose of this section is to describe the Navigation System Evaluation Model/PON model input data. The inputs will be discussed in terms of their content, with minimum emphasis on input format. The input formats as they currently exist were designed for SCI (Vt) use, with the objective of providing efficient debugging and initial model tuning capability. Prior to model implementation, considerable attention will be paid to input requirements and formats, to permit convenient use of the model by USCG personnel. A part of this effort is discussed in Section 3.6.5.

It is appropriate to note that this section addresses only user input data, which is only a subset of a data upon which the model operates. The model contains much additional data, in the form of error values, control parameters, etc., but these need not be input by the user. They are contained in the model's data base.

The user input is intended to serve two basic functions: (1) to provide to the model non-standard information (such as the specific buoy configuration to be considered) which cannot be efficiently prestored within the model, and (2) to identify to the model which of its internal data sets and logic/processing options (such as vessel type and associated dynamics data) are to be used.

The primary data items which are required by the NSEM and/or the PON can be categorized as follows:

(1) harbor module data
(2) vessel data
(3) situation "modifiers"
(4) aid to navigation configuration data

In the following paragraphs, the data items required in each of these categories are discussed.

Harbor Module Data Inputs

The model currently recognizes three general types of harbor modules:

(1) straight channel
(2) channel bend
(3) channel entrance.

"Obstructions" are treated as integral parts of these modules, rather than as a separate module type. It is appropriate to mention that these categories will (ultimately) be utilized by the NSEM portions of the overall model, for the purposes of identifying buoy configuration guidelines, previous model results and mariner requirements. The PON submodel, however, is not constrained by specific module types. Any arbitrary channel design can be modeled (subject only to dimension limits on internal arrays).

The user input for harbor module definition consists of the following:

(1) Module type.

(2) Specific data set identifier. At the user's option, this could include the actual channel name and/or location, and would permit unique identification of the data set, by both the model and user.

(3) Channel boundary coordinates. Ultimately, various standardized channel configurations may be prestored in the model and either used directly or modified by user input. At present, however, all channel boundary data is input by the user. This provides greater user flexibility, which is useful for initial sensitivity analyses.

(4) Obstruction data. This is also input in terms of location coordinates.

(5) Depths (within the channel, outside the channel).

Vessel Data

The vessel data requires very detailed definition in order to satisfy the processing requirements. A good deal of this information is pre-stored in the model, however, and need not be input by the user. As a result, the user input for vessel definition consists only of the following:

(1) Vessel identification code. This uniquely identifies to the model all appropriate vessel parameters and subroutines. The required complexity of the code is a function of how many vessels and variations thereof are pre-stored. (The code currently has no particular significance.)

(2) Vessel speed and nominal maximum rudder deflection. These values are not pre-stored by the model, since it is expected that the model user will desire to evaluate various speeds and maximum rudder values, for a given vessel type.

(3) Vessel desired track. Considerable thought was given as to whether or not a desired track should be input or

derived internally. It was established that, at this stage of the study, model derivation of the desired track would be difficult to implement and of uncertain value. Further analysis of the need for this input will be made in Phase II.

The desired track is defined, via user input, as a series of straight and curved segments, in terms of x-y coordinates and track segment heading change. The heading change parameter is used to determine the curvature (radius) of curved segments. It is appropriate to note that the desired track, as input, is specified only in terms of geographical characteristics; the vessel heading, or other pilot commands, needed to maintain the desired track are derived within the mariner model.

Situation Modifiers

The situation modifiers currently input and processed by the model are as follows:

(1) current (direction and velocity)
(2) visibility
(3) day/night code.

Aid to Navigation Configuration Data

With regard to visual aids not on the vessel, the model currently accepts and utilizes only buoy information. USCG ranges can also be accommodated, by means of inputting the front and rear ranges in the same manner as buoys. Modeling sophistication which recognizes the difference in information between buoys and either half of a range has not yet been implemented. The input data currently consists of the following:

(1) buoy identification number
(2) location coordinates
(3) lighted/non-lighted indicator.

The inputs described above define a particular "situation" to be evaluated. The NSEM is currently structured to process multiple situations, wherein more than one vessel type, speed, maximum rudder or desired track can be considered. Specifically, for a given harbor model, up to three desired tracks can be evaluated, each with as many as five vessels, speeds, etc.

3.3.3 Process of Navigation Model Structure

The process of navigation, as considered here, consists of the steps involved in guiding a vessel safely and efficiently in and out of various harbors and coastal waterways. This process is modeled by the interrelated functions which are depicted in the block diagram of Fig. 3.4. This model, as developed in a digital computer program, is described in detail in Appendix F.

There are two humans modeled in the PON--the pilot (or master) and the helmsman. The other model elements include the vessel and propulsion dynamics and characteristics, the harbor geometry and environment, the on board instruments, the aids to navigation, and various sources of error and disturbance that cause this system to be random rather than deterministic in nature.

As is seen in Figure 3.4, the pilot is split into three functions--state estimator, decision maker and commander. The most important link in this model is the relationship between the aids-to-navigation and the state estimator portion of the pilot. The purpose of developing the model, as a single entity, is to examine this relationship and its effect on overall system performance and pilot workload.

The following subsections summarize the pilot and helmsman models, the vessel dynamics, and other pertinent features of the PON model.

3.3.3.1 Model Structure - Pilot and Helmsman

For steering the vessel, the relationship exists where the pilot gives instructions to the helmsman in two forms--rudder commands and heading commands. For these two situations, the pilot acts in two roles. When he is giving direct rudder commands, he is in an active "controller" model. He is then modeled by three sequential but interrelated functions (indicated in Figure 3.4). These are as follows:

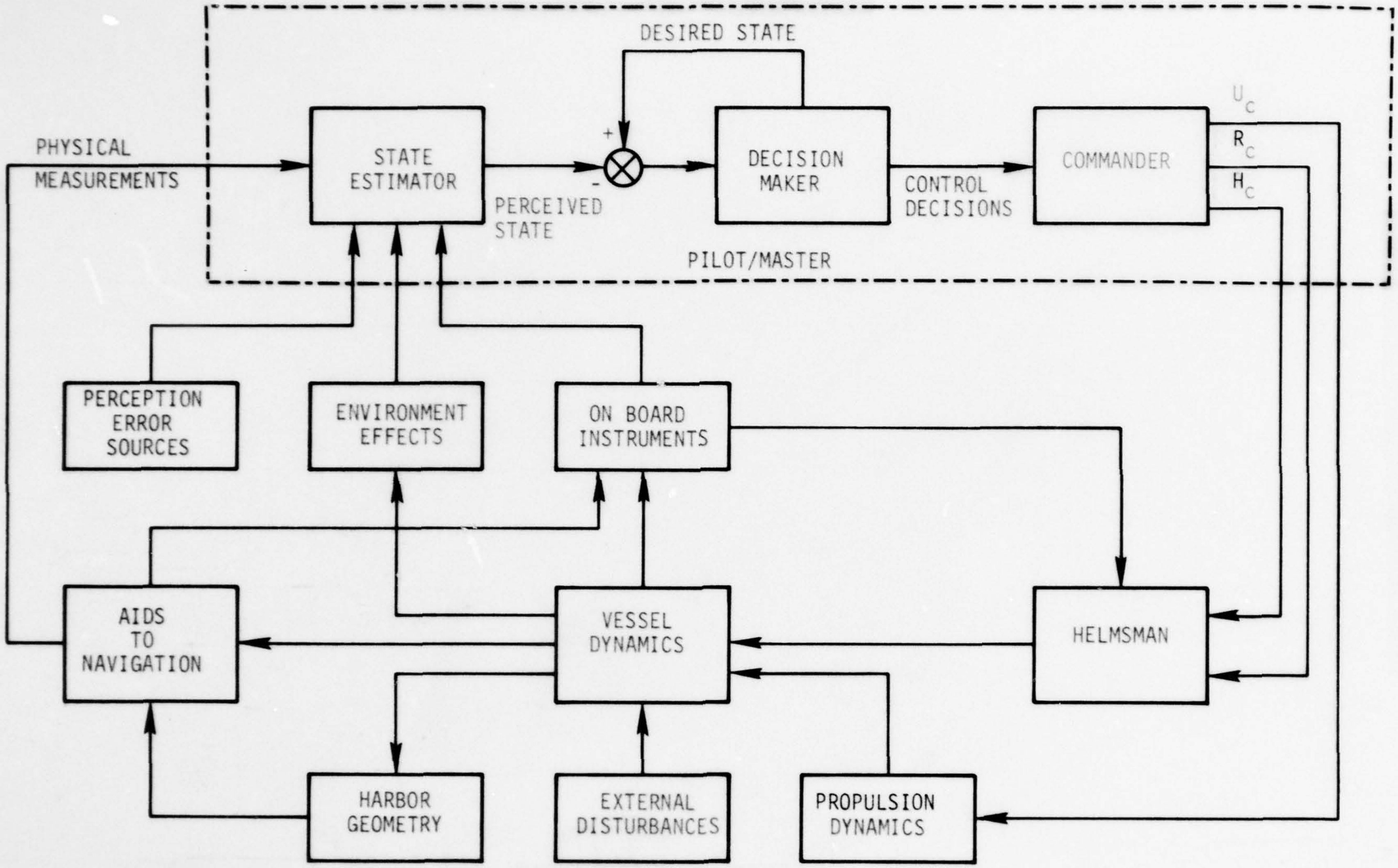


Figure 3.4 Process of Navigation Model

(1) Estimator - determination of the state of the vessel with respect to the desired course and other decision variables.

(2) Decision maker - determination of what action, if any, must be made to correct the vessel situation or to make a regular change in course.

(3) Commander - identification of rudder setting or desired heading, which, when provided to the helmsman, will yield the required vessel response.

When the pilot gives the helmsman a heading command, in contrast to a rudder command, the three active functions, in a more limited scope, are then enacted by the helmsman. The pilot resorts to a passive or "monitor" module. He will resume an active role (i.e., issue a new command) when: (1) a change in course is desired, (2) a drift in vessel motion is detected due to current, wind or random perturbations, or (3) the helmsman fails to hold proper heading.

When the pilot is in the active role, the helmsman does only as instructed by the pilot. When the pilot is in a passive role and has given the helmsman a heading command, the helmsman proceeds to steer to hold that heading. He then must: (1) judge the error in the vessel heading and heading rate, (2) decide if a compensating change in rudder setting is required, and (3) input this rudder change directly through the helm.

The types of navigation situations that the pilot and helmsman are designed to resolve in the current PON model include:

(1) Making a course change (as around a bend; including turn planning, initiation, monitoring and termination).

(2) Returning to course.

The PON model will be extended in Phase II to simulate other pertinent navigation functions (as described in Section 3.6.1).

In the following paragraphs, details of the pilot state estimator, decision maker/commander, and helmsman submodels are summarized.

3.3.3.1.1 State Estimator

The purpose of the State Estimator is to mimic the pilot (or mariner) role of estimating, in real time, the state of the vessel. The pilot accomplishes this task by first viewing the visual aids and vessel displays. These perceptions are correlated with vessel state by means of:

(1) relying upon a previously learned relationship between perceptions and state,

(2) implicitly performing various mental computations in order to "mathematically" deduce vessel state, or

(3) a combination of these procedures.

Depending upon the specific situation and pilot, there may be considerable uncertainty regarding which of the above procedures are utilized. It is important to note, however, that for the modeling approach adopted, this uncertainty need not be resolved and the State Estimator need not perform this function in the exact same way as the mariner. In order to satisfy the modeling requirements (and associated study objectives), the State Estimator must:

(1) utilize the same basic perceptions as are used by the pilot, and

(2) generate estimates of the vessel state with the same general level of accuracy as is obtained by the pilot.

It is appropriate to note that the State Estimator does not identify which state variables are important, nor does it identify suitable mariner control action; these functions are relegated to the "Decision" and "Command" submodels, respectively. These submodels are described in the next section.

Within each simulation time increment, the State Estimator supplies to the subsequent pilot submodels estimates of the following pertinent vessel state variables:

(1) Cross-Track Deviation
(2) Cross-Track Deviation Rate
(3) Along-Track Position
(4) Along-Track Position Rate
(5) Heading
(6) Heading Rate
(7) Rudder Position.

The state estimation process is composed of five basic functions:

(1) Identification of information available,

(2) Estimation of anticipated error variances associated with the available information and identification of information to be utilized,

(3) Determination of weighting factors (to be applied when redundant information is available and used),

(4) Generation of the actual observations, and

(5) Combining of observations to form final state estimates.

Figure 3.5 provides an overview diagram of the State Estimator. Each of the basic estimator functions is described in brief in the following paragraphs.

<u>Identification of Available Information</u>

The State Estimator is currently designed to utilize (visual) information from buoys, USCG ranges and selected vessel displays (compass, rudder indicator and speed log). The capability to process other available information, such as audio information, radar, electronic aids and relative position to other vessels, will be incorporated into the model in Phase II.

Vessel displays are always considered "available." Although the capability to assess the impact of display malfunctions exists, this is not considered a first order study interest.

The current constraints on buoy/range availability are as follows:

(1) They must be within the prescribed visibility limits (a simulation input),

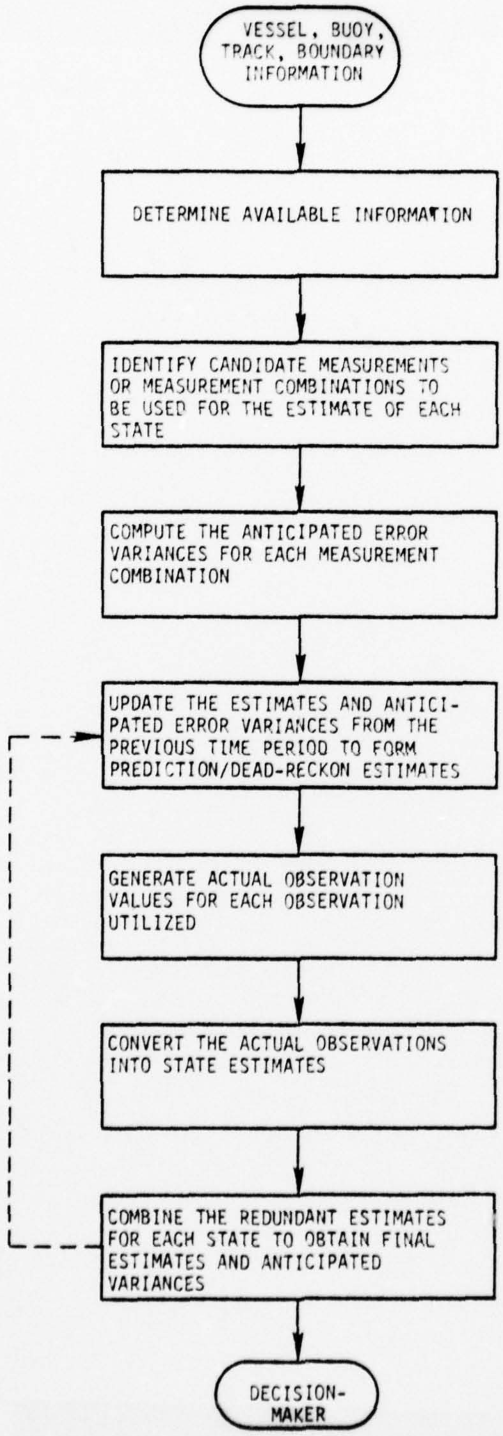


Figure 3.5 Mariner State Estimator Overview

(2) They must not be behind the vessel, and

(3) For "nighttime" simulations, they must be lighted.

Buoys (and ranges) provide distance information, angles between buoys, angles off the bow, and angle rates. The specific manner in which this information is used is a function of the particular state variable being estimated (as discussed below).

Identification of Information Utilized

For each state variable, special logic has been designed which processes the available information in order to identify that which is utilized. This logic varies in complexity as a function of the variation in the type and amount of information which might potentially be used. The following paragraphs summarize the types of information utilized for the estimation of each variable:

(1) Cross-Track/Along-Track/Heading/Heading Rate. The estimation of each of these variables is accomplished by combining a prediction or dead reckoning estimate with a "primary" estimate, and (except for heading) a "secondary" estimate. The dead reckoning estimate is based upon the previous estimates of the state and their rates. Logic to identify the sources of the primary and secondary estimates is unique for each variable. For cross-track and along-track estimates, the logic searches for candidate LOP pairs. (More LOP's than are necessary are obtained, and the weighting logic, described in the next section, is used for the final "primary/secondary" selection). For heading rate, the two buoys closest off the bow are selected. For heading, only the compass is used.

(2) Cross-Track Rate/Along-Track Rate. To estimate these variables, estimates emanating from approximate equations relating vessel position rate to vessel heading, speed and water current are utilized. From a behavioral point of view, this implies that the pilot's perception of cross-track or along-track rate stems primarily from knowledge of his heading relative to the track, and an intuitive understanding of the effect of current.

Computation of Anticipated Error Variances and Multiple Estimate Weighting

In most instances, a pilot has redundant information by which state estimates can be obtained. He makes a decision, consciously or otherwise, as to which portion of the information to use and how much to rely on one information source as compared to another.

Multiple or redundant state variable estimates (dead-reckoning, primary, secondary) are weighted according to the model's representation of the "pilot's confidence" in each. This confidence is a function of how well the pilot feels he can measure (perceive) various information parameters (distances, angles, etc.), and his understanding of the impact of estimation errors in the particular situation geometry. Thus, the selection of which information sources to utilize and their associated weights is based upon the pilot's "anticipated" errors (variances thereof).

The model accepts two totally separate sets of error variances: "anticipated" error variances (which form the basis for the weighting), and "actual" error variances (which are used by the simulation logic to generate actual observation errors). While the initial model executions utilized equal values for anticipated and actual error variances (implying that the mariner has a correct understanding of his perception ability), the capability exists to alter these values as a part of model tuning or calibration, and/or in the event that data are obtained which indicate that anticipated and actual errors are not equal.

Anticipated error variances are input for each type of observation (angle off bow, angle between buoys, distance, compass, speed). Transformation of these errors into anticipated state estimation errors is accomplished algebraically. Multiple observation estimates are linearly combined with weights inversely proportional to their variances. This combining technique produces minimum variance estimates, and this degree of optimality is considered appropriate when attempting to mimic the performance of a trained pilot. Computation of the anticipated variance of the

final (combined) estimates is also performed. These results are utilized to derive suitable error variances (i.e. weights) for the dead-reckoning estimates for the subsequent time period.

In addition to the use of both anticipated and actual error variance data, another key element of the error modeling is the partitioning of the errors into random and bias terms. Specifically, all errors have the following components:

(1) a bias; randomly selected at the beginning of each transit,

(2) a "common" error; randomly selected for each time period, and

(3) a random noise error.

The subdivision of errors into random noise and bias components is a standard simulation technique. It is used to account for the fact that human operator errors, and many instrument errors, contain a significant bias term, often of greater magnitude than the noise error. In the current simulation, an additional error component has been added, referred to as a "common" error. This error functions as a bias applied to all observations of the same type made at the same time. This provides for a statistical mechanism to account for the fact that the comparison of equal distances or equal angles can be very accurately performed. For example, the difference between two distances can be more accurately estimated (perceived) than either of the distances by themselves. In the current implementation of the model, this decrease in error is accounted for by having the common errors of the difference cancel out. Error variance is thereby reduced, and this phenomenon has been suitably taken into account in both the actual and anticipated error logic.

Measurement Generation and Combination

Measurement generation and combination is a straightforward process. Given that the specific segment of information and the associated weights to be used have been identified, the actual

pilot observations are obtained by computing the "true" observation values and adding randomly selected errors (based on the respective actual error variances). Based upon the situation geometry, the actual observations and combinations thereof are transformed into state variable estimates according to known geometric/physical relationships. Multiple observations are averaged by their weights.

3.3.3.1.2 Decision Maker/Commander

The pilot Decision Maker role consists primarily of two modes--the Monitor mode and the Controller mode. These modes are reflected in the block diagram shown in Figure 3.6.

Initially, when the pilot is in the decision making role, he is comparing his estimate of the vessel state and other variables to what he knows the nominal vessel track should be. The pilot first compares his state to where his next change in course is. If the nominal course change is still some time off, the pilot compares his vessel state to what he considers to be the nominal path he wishes to follow, and issues commands to the helmsman as necessary to hold track.

The pilot functions as a monitor when the previous estimated state of the vessel was perceived to be satisfactory and the helmsman has been instructed to hold a given heading. Actual control of the vessel is being handled by the helmsman. As the pilot monitors progress, he continuously assess vessel status. If the pilot perceives no problem, he continues with the status quo and the helmsman continues to function as before.

If the pilot decides that a problem exists or that a course change is required, he then takes over command. He switches mentally to an active "Controller" mode. The pilot's next decision involves identifying the type of vessel maneuver to initiate. Associated with each maneuvering problem is a procedure that the pilot has learned to resolve the problem. The maneuver problems and the learned solutions can be thought of collectively as a

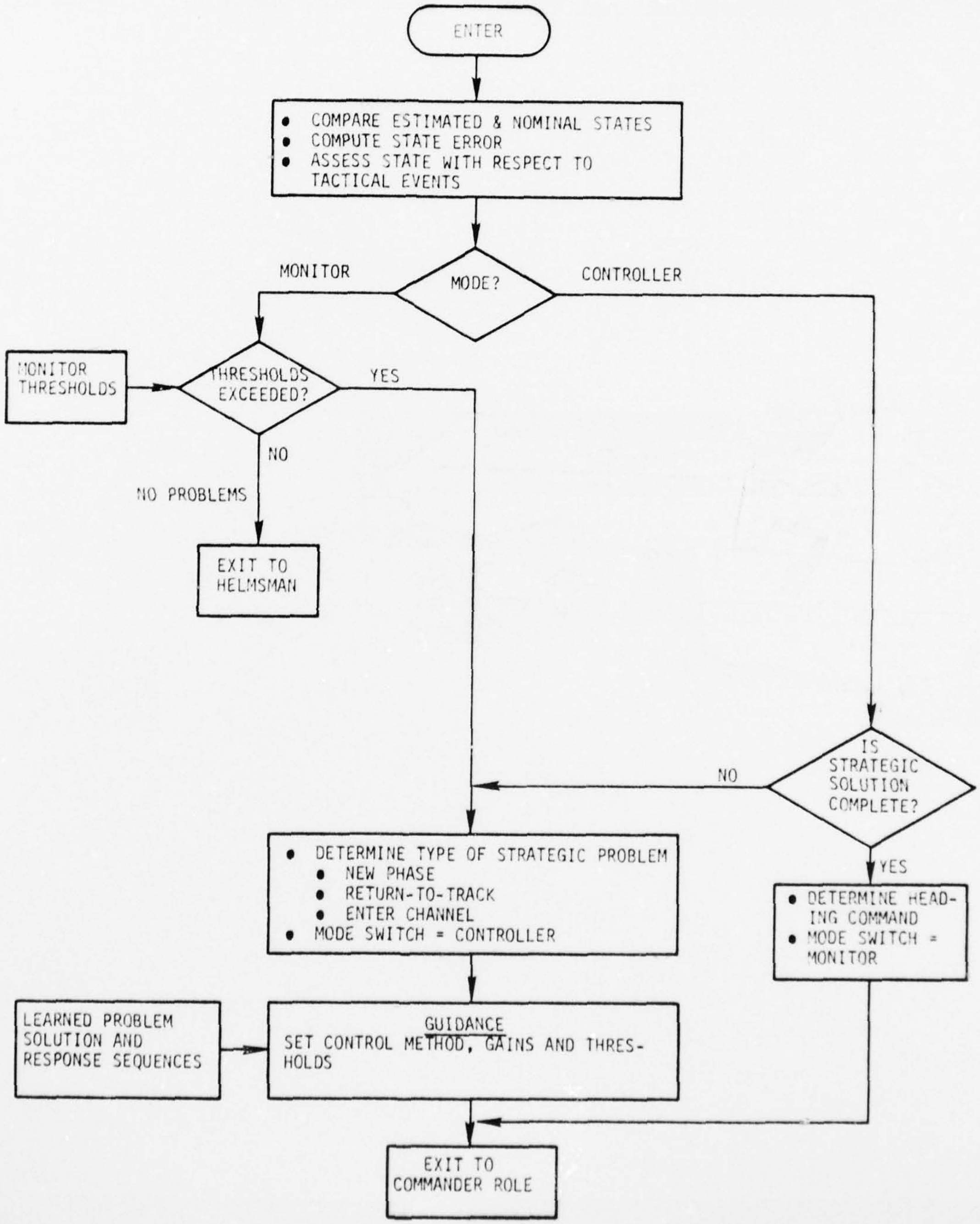
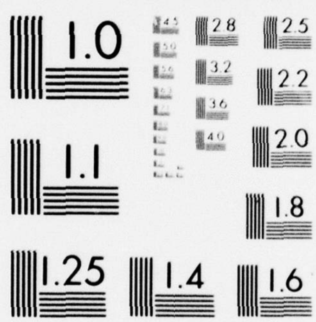


Figure 3.6 Block Diagram of Pilot Decision Maker Role

AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)
MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A
UNCLASSIFIED USCG-D-38-78 NL

2 OF 6
AD
A059891


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

catalog of procedures existing in the pilot's mind. This catalog is referred to here as the "Guidance Function." During the decision making process, the pilot uses the identified problem/corrective maneuver to identify the guidance procedure to follow in his subsequent Commander role.

The Phase I study has focused on two general maneuver problems--negotiating bends and returning-to-track. In the subsequent phase, other strategic and tactical situations will be modeled and examined.

When in the Controller mode, the pilot's primary concern is deciding how much rudder angle to command, and when the next rudder command should be given. For negotiating a bend, he decides when to command that the rudder be deflected, when to reverse directions, and when the rudder should be set to zero.

When in a controller mode, there are two other types of decisions that the pilot may make. The first is the decision that the maneuver is complete. If this decision is made, the pilot decides what heading the vessel should subsequently maintain. This heading is based on information contained in the chart of the channel, the prevailing current, the vessel speed, and the pilot's general knowledge of the channel. This heading is given to the helmsman, and the pilot then mentally switches back to the Monitor mode.

The second type of decision is made when the vessel is going around a bend. Here, if the vessel drifts off the nominal track far enough, the pilot decides to add the return-to-track commands to the nominal commands used to negotiate the bend.

When a maneuver is required, the Commander function refers to a catalog of guidance functions. As each maneuver progresses, the Commander issues the rudder command sequence from the catalog as is deemed appropriate. If a return-to-track maneuver is being enacted, the commands consist of a series of rudder angles which will cause the vessel to merge into a threshold around the nominal path. If a bend is being negotiated, the commands will consist first of a rudder deflection to begin the turn, and then a setting

of the rudder deflection in the opposite direction to stop the turn. When both of these strategic maneuvers are finished, the Commander will issue a heading command for the helmsman to hold.

3.3.3.1.3 Helmsman

When the pilot is in an active Controller role, he issues rudder commands directly to the helmsman. After a small time delay, the helmsman inputs these commands directly to the helm. These commands are physically limited by the command limit of the helm.

When the pilot is in a passive Monitor role, he will have issued a heading that he wishes the helmsman to follow. In this case, the helmsman must establish his own rudder deflection commands. The helmsman's sources of information for heading and heading rate are the same as the pilot's; the ship's compass, with its measured heading, and the relative motion of buoys. The helmsman determines the difference between the desired and estimated vessel headings. He uses this difference plus his estimated heading rate to formulate an appropriate sequence of rudder commands to hold the desired heading.

3.3.3.2 Vessel Dynamics and Other Non-Human Elements in the PON

The non-human elements which make up the Process of Navigation model, as depicted in Figure 3.4, are listed in further detail in Table 3.2. The elements include the vessel dynamics, the external aids to navigation, the on board sensors, the vessel rudder and throttle dynamics, environmental effects, the harbor geometry, and various other inputs that contribute to the process of navigation. These categories are defined in more detail in Appendix F, with regard to how they are included in the PON model.

It is of interest to summarize here the characteristics included in the modeled vessel dynamics. The form used for the vessel dynamics model is characterized by:

(1) three degree-of-freedom motion (yaw, sway, surge), represented by three nonlinear differential equations; and

(2) a truncated Taylor series expansion of the hydrodynamics forcing functions, retaining only those terms which are of significance in describing vessel motion in shallow waters.

This form was selected for the following reasons:

(1) It is computationally efficient.

(2) It provides an accurate representation of the vessel's motion, particularly where pitching motions are minimal.

(3) Its structure is directly expandable to include additional effects (bank suction, etc).

Table 3.2

Non-Human Model Elements

Category	Elements
Vessel	Dynamic equations Hydrodynamic coefficients Shallow water effects Loading effects Wind and aerodynamic effects Vessel dimensions; wheel house location Engine characteristics
Aid to Navigation	Geometric locations and dimensions Types of navigation information Error sources and equations
On Board Sensors	Types and associated information Error sources and equations
Rudder and Throttle	Equations and coefficients
Environmental Effects	Current Wind Sea state Precipitation Cloud cover Time of day
Harbor geometry	Channel elements - bends; straight passage; entrance; anchorage Shoreline features Obstacles - bridges; sunken vessel, sand bar Depth geometry
Miscellaneous Elements	Charts Inter-vessel communication Traffic and weather advisories Rules and regulations Local custom Other vessels and their relative motion

Three differential equations are used to describe the vessel's motion with respect to a reference frame which is aligned with the vessel's axis, and centered at the vessel's center of mass. The forces and moments which drive these equations are of three types--hydrodynamic, propulsive, and aerodynamic. Three more differential equations are then used to determine the vessel's along-track and cross-track position components and heading. The effect of current magnitude and direction are added into these equations.

The hydrodynamic coefficients entering the vessel dynamic equations are experimentally determined, and the conditions under which such experiments are conducted determine the range within which the coefficients are valid. As an example, it may be important for a particular application that the coefficients used in the PON model represent data collected from shallow water tests.

Restricted channel effects (bank suction, etc.) can be added directly as polynomial terms in the distance from the channel boundary. The coefficients for such terms are again sensitive to experiment conditions (shape of the channel boundary, hull shape). As a result, model fidelity is good only under restrictive operating points. Since pilot control actions will attempt to account for such effects as bank suction, the sensitivity of the overall PON model to the fidelity of this data is reduced somewhat. Restricted channel effects are not included in Phase I, due primarily to the unavailability of data.

Propulsion control (i.e., speed changes commanded by the pilot) was not utilized for Phase I. Consequently, non-steady propeller effects are not included in the model at this time. In actuality, temporary bursts of propeller RPM are used as a quick-response course changer (kick-over) at low speeds. This phenomenon will be included for Phase II. The effects of bow thrusters were not included, as these are ineffective above about four knots.

Aerodynamic effects depend on the effective profile presented to wind forces; this effective profile, in turn, is a function

of vessel shape, orientation, and loading conditions. In Phase II, these effects will be included in a simplified manner.

For the PON model studied in this first phase of this effort, the characteristics of an 80,000-ton tanker were utilized. A plot of this vessel's motion as a function of various rudder angles is shown in Figure 3.7. It is seen from this plot that the motion of this vessel following a fixed rudder deflection can be characterized as a straight line path followed by a circular arc. The exact path followed is dependent upon rudder deflection angle and not on initial forward speed. Thus, for a given vessel, its dynamic motion can be controlled by rudder input without regard to speed. More details on this vessel's dynamic characteristics are presented in Appendix F.

3.3.4 Model Output (Vessel Safety and Traffic Facilitation Measures)

The purpose of this section is to describe the output of the Navigation System Evaluation Model and the preliminary vessel safety and traffic facilitation measures thus far developed. It is appropriate to note that not all of the performance measures identified have been quantified and/or incorporated into the current model. In some instances, adequate time and resources were not available for this purpose. In other instances, some additional performance measures could have been incorporated into the model, but it was known that calibration and/or preliminary validation would not be feasible within the time constraints; hence, these efforts were not undertaken. However, the development of the overall modeling approach and the detailed model design activity were performed with a clear understanding of the types of performance measures which will ultimately be required. Incorporation of additional performance measures is, therefore, expected to be a straightforward task (in terms of model integration).

This section is divided into two parts. The first part (Section 3.3.4.1) presents a brief description of the types of performance measures which are expected to be incorporated into

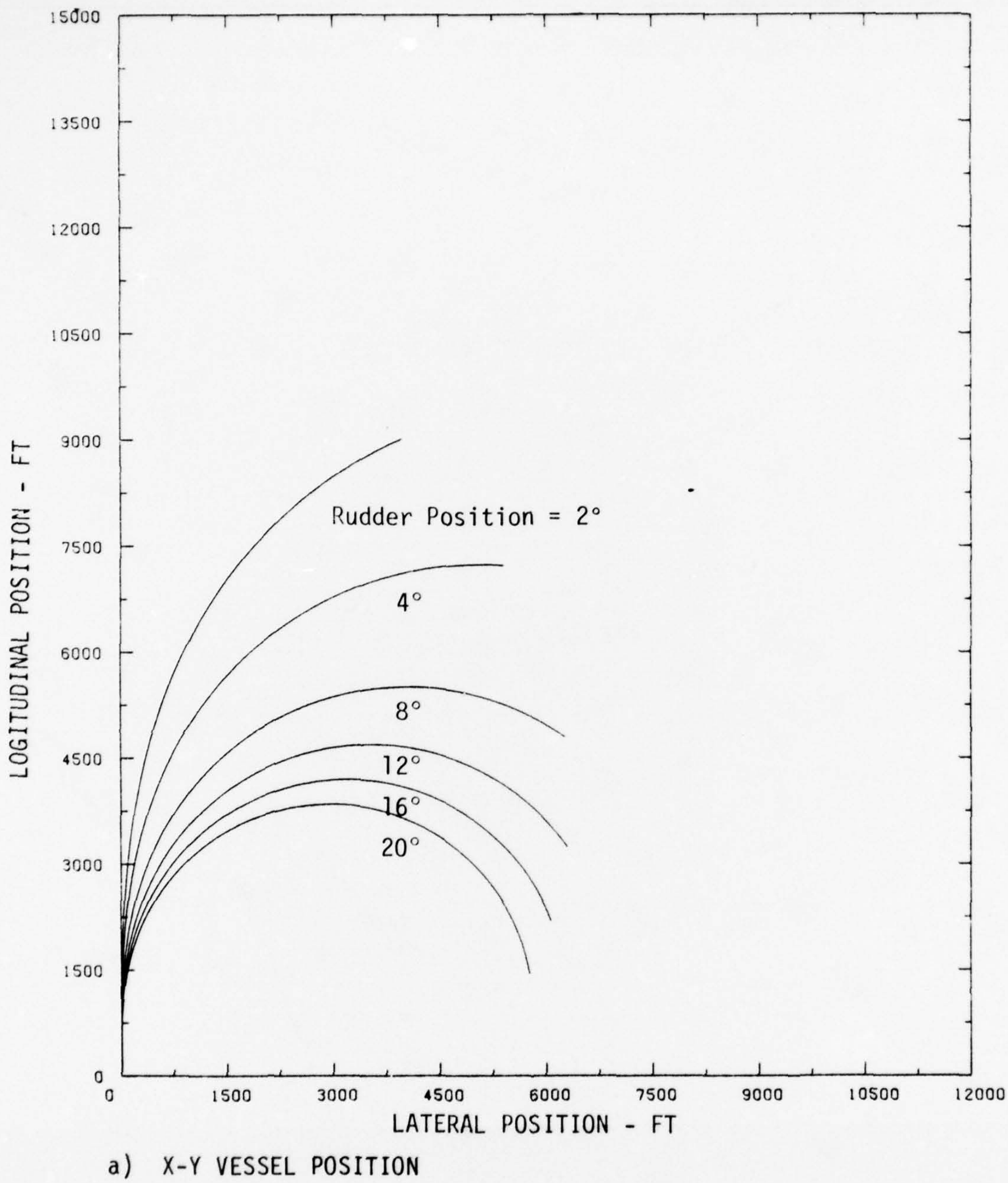


Figure 3.7 Plots of 80,000 Ton Tanker Turning Characteristics as a Function of Rudder Angle for an Initial Speed of 8 Kts.

the model at the outset of the Phase II effort. These are presented for the purpose of clarifying the intended SCI (Vt) approach toward the development of performance measures, and also for the purpose of exposing the model's computational capabilities in this regard. The subsequent subsection (3.3.4.2) presents, in detail, the outputs which the model currently provides.

3.3.4.1 Vessel Safety and Traffic Facilitation Measures Identified in Phase I

The following paragraphs describe the VS+TF (performance) measures which are recommended for inclusion into the model early in the Phase II effort. These do not constitute all of the performance measures to be identified and evaluated in Phase II; but, rather, are intended to serve as the starting point for Phase II performance measure development.

Safety Measures

Within the context of this study, the fundamental measures of vessel safety emanate from the distribution of cross track deviations. Cross track deviation statistics are currently being computed, but these results are not being transformed into more specific or direct safety measures. Early in Phase II, logic will be added which will utilize the cross track statistics to estimate probability of grounding. These statistics will also include vessel size, which is not currently being considered. Statistics will also be output to permit an analysis to be made of the form of the cross track distribution. The assumption that cross track deviations are normally distributed, for example, may well not be appropriate.

It is expected that the form of the cross track distribution and its statistics will produce usable measures of safety. However, these measures may have deficiencies for either of two reasons. First, for typical buoy configurations, the information available to the mariner is reasonably accurate at the channel

centerline and near its boundaries, but is less accurate in between. Thus, as a grounding occurs, the information available to the mariner changes, as will his performance. The ability to accurately extract the effect of this phenomenon, via straightforward Monte Carlo simulation and analysis of cross track distributions, is somewhat uncertain. Secondly, cross track deviation, in and of itself, is not the total measure of danger (or safety). Other factors of significance include the vessel orientation, actual motion, and maneuvering capability (as well as information available).

Lastly, it is also envisioned that model logic will be added in order to produce cross track deviation vs. heading (matrix) information, as shown below:

CROSS TRACK DEVIATION
(FROM DESIRED TRACK, IN FEET)

VESSEL ORIENTATION RELATIVE TO TRACK ORIENTATION		...	(-50,-25)	(-25,0)	(0,25)	(25,50)	...
	-						
	-						
	-						
	-2.5°, -.5°		RATIO OF NUMBER OF SAMPLE POINTS TO TOTAL				
	-1.5°, -.5°						
	-.5°, .5°						
	.5°, 1.5°						
	1.5°, 2.5°						
	-						
	-						
	-						

Information of this type may also provide an input to the development of safety measures; particularly since potential safety measures, if based on information of the above type, could be evaluated and calibrated "off-line," without continued model execution.

Convenience (Workload) Measures

There are two main categories of workload which must be considered; mental workload and control workload. Mental workload deals with the mariner as a monitor/decision maker, i.e. the effort involved in measuring and estimating the quantities of interest (Estimator Submodel) and deciding what control action to take (Decision Submodel). Mental workload increases with the number and complexity of visual cues, the complexity of the mariner's intentions, and the sophistication of the decision or "indifference threshold" logic applied. Mental workload also increases with the amount of "lead" or anticipation attempted by the mariner; for example, heading rate is more difficult to estimate than present cross-track deviation because it requires anticipation in order to derive rate of change. Control workload is affected by the precision requirements of the control performance criteria, and also by the mariner anxiety level; for example, a high anxiety situation will lead to more frequent control application.

Further, tradeoffs in these types of workload exist. For example, a mariner utilizing heading rate information incurs a higher mental workload than when cross-track deviation is use; but the heading-rate strategy will likely exhibit reduced control workload due to the reduction in anxiety associated with the additional "lead" or anticipatory information contained in the heading-rate estimate. Experimental studies have indicated that those control strategies involving anticipatory information exhibit improved performance and, in fact, are preferred by human operators.

The model currently computes what may be referred to as the standard measures of control workload (number of commands given, average rudder deflection, etc.). In the first part of Phase II, specific attention will be paid to the incorporation of mental workload measures. As a starting point, the model logic will be augmented to provide matrix output as shown on the following page.

TYPE OF INFORMATION

		1	2	3	4	. . .	TOTAL
	1						
	2						
STATE	3	NUMBER OF TIMES EACH TYPE OF INFORMATION USED FOR THE ESTIMATION OF EACH STATE					
	4						
	.						
	.						
	.						
	TOTAL						

This matrix identifies the number of times each type of information (distance, angle, rate, etc.) is utilized for the estimation of each state. Ultimately, individual workload measures can be associated with each matrix entry, and overall measures of mental/estimation workload can be developed and refined. In a similar manner, statistics can be tabulated regarding the percent of the time that various monitor or control strategies are being used.

Efficiency Measures

As a result of the interviews and related study efforts undertaken as a part of Phase I, the development of efficiency measures was de-emphasized (deferred). All of the "efficiency" considerations of particular interest are more appropriately addressed, initially, within the area of safety. Whether or not vessel movement is restricted due to the inability to pass, lack of daylight and/or poor visibility is governed by the safety implications. It is somewhat premature to attempt to develop usable efficiency measures until accurate safety measures and acceptable bounds on the safety measures are developed. When this is accomplished, the impact of aids-to-navigation on efficiency can be readily evaluated.

3.3.4.2 Model Output

The purpose of this section is to describe the output currently made available by the Navigation System Evaluation Model. The reader may also refer to Appendix G, wherein a sample page of each type of model output is presented.

It is necessary to mention that, at this stage of model development, specific attention has not been given to the design of self-explanatory and cleanly formatted output. Output formats will be upgraded significantly prior to model delivery and implementation.

Each basic type of NSEM model output is listed and described in the outline below.

A. Detailed Time Period Output

This output can be made available for each time period of each simulation, or at selected time intervals. Its function is to present the complete State Estimator results. The data items printed include the following:

1. Time period.
2. True* vessel states.
3. Buoys available; distances and angles off the bow.
4. LOP orientation and anticipated variance, for all LOP's considered.
5. For each state:
   a. Final estimate and variance.
   b. Buoys/LOP pairs used.
   c. Primary, secondary and dead-reckoning estimates, variances and weights.

*The term "true" is used synonymously with "actual"; no reference is being made to true versus magnetic values.

B. Detailed Transit Output

This output is a summary of the detailed time period output. The more important data items are listed as a function of time. These items include:

1. True value, estimated value, and anticipated standard deviation for each state.

2. Pilot and helmsman rudder command.

3. Desired heading and heading error.

4. LOP types and buoys used for cross-track and along-track, both primary and secondary.

C. Transit Summary Data

A short transit summary output is also provided, which is typically useful when longer Monte Carlo runs are made, and voluminous output is not needed or desired. The transit summary statistics include the following:

1. Average estimation error (averaged over all time periods), average error absolute value and average anticipated standard deviation for each state.

2. Average weights for primary, secondary and dead-reckon estimates for cross-track, along track and heading rate.

3. Number of times pilot command changed.

4. Percent of the time the vessel was under active pilot control (in contrast to the helmsman maintaining a heading).

D. Detailed Monte Carlo Statistics Data

Detailed information is printed output encompassing all of the statistics (of those currently available) which might ultimately be of analysis interest. These items are listed as a function of time, and include:

1. Mean value, standard deviation, third and fourth moments of the true state values.

2. Average estimation error, average absolute value of the error and average anticipated standard deviation, for each state.

3. Average primary/secondary/dead-reckon weights for cross-track and along-track.

4. Desired heading, averages of the pilot and helmsman rudder commands.

E. Overall Monte Carlo Summary

A final output page is provided which is intended to summarize an overall Monte Carlo execution. This output encompasses:

1. Cross-track, along-track, heading rate estimation statistics:

   a. Average error.

   b. Average absolute value of the error.

   c. Error standard deviation.

   d. Root mean square error value.

2. Cross-track performance:

   a. Average cross-track position.

   b. Cross-track standard deviation.

3. Pilot-vessel performance:

   a. Average rudder.

   b. Rudder standard deviation.

   c. Root mean square rudder value.

   d. Average number of pilot/helmsman rudder command.

   e. Average percent of time vessels were under active pilot control.

The current NSEM model also provides CALCOMP computer plots, which provide a convenient illustration of several of the run statistics of primary interest. These plots are presented and discussed as a part of the analysis of results in Section 3.4.

3.4 PRELIMINARY MODEL APPLICATION RESULTS

As has been mentioned, one objective of the Phase I effort was to develop a functioning NAVAID System Evaluation/Process of Navigation Model. This was accomplished, and the model was then exercised for several harbor module/buoy configuration combinations. This activity was undertaken, and the results herein described, for the following three reasons:

(1) to demonstrate that the model, even in preliminary form, can be used to produce realistic and valid results,

(2) to convey how the model results can be used to identify the experiments which are required for model calibration and validation, and

(3) to clarify the output of the model, in the context of its ability to support the derivation of establishment/ disestablishment criteria.

With regard to (1) above, a distinction is made between obtaining "valid" results versus demonstrating that the model can (ultimately) be used to obtain valid results. The latter statement best reflects the objectives of the Phase I study. The Phase I model does produce valid results, but this is at least in part due to the fact that the model has been tuned so as to produce results which are consistent with results from other sources (such as past experiments) which are presumed valid. Validation of the model will ultimately permit (judicious) reliance upon the model results as being valid, independent of direct external substantiation; but this is strictly a Phase II activity.

As mentioned, the primary interest in Phase I is to demonstrate validity of the modeling approach; i.e., that the model is of a form that can be used to produce the required results, and valid results. Within Phase I, this demonstration is a somewhat subjective process. Demonstration, or testing of model validity, is accomplished by:

(1) scrutinizing all results in order to identify apparent anomalies, reversed sensitivites, etc.

(2) determining why the anomalies were obtained, and

(3) identifying the additional model capabilities, enhancements, "fixes," etc., which are needed.

If the manner in which the additional capabilities must be included in the model is consistent with the modeling techniques and the general framework of the model, then this is very positive evidence of validity of the approach. On the other hand, if additional capabilities are needed which are not feasible within the adopted model framework, this would be evidence that the approach is not sufficiently comprehensive. Problem solution would then depend upon externally derived results or auxiliary computational algorithms. Correlation of the results might be more difficult, the evaluation process might be encumbered and, in general, a greater validation risk could exist. Based on SCI (Vt) analysis of the results produced to date, no model limitations have been found which cannot be easily remedied within the basic modeling approach adopted. The reader is encouraged to perform a similar analysis as the model results in the following subsections are presented.

3.4.1 Analysis Results Overview

The model application results presented here emanate from an analysis of simulated passages under both ideal and realistic situations. The ideal cases are necessary to enable isolation of the factors which cause certain model behavior. The realistic cases are necessary to establish confidence in the process of navigation model, namely, that the model produces reasonable pilot estimates and actions under real-world conditions.

This preliminary analysis is divided into two phases--model component analysis and composite analysis--as illustrated in Figure 3.8. The component analysis addresses the isolated component performances, preliminary parameter selection and sensitivity to variations in parameters and geometry, for the two primary

components of the mariner model--the estimation process and the decision/control process. These two components are defined in Figure 3.9. The composite analysis then examines the combined, closed-loop behavior of the mariner estimation, decision and control models in a variety of test situations. Monte Carlo techniques are used in the composite analysis to examine model statistical performance aggregated over a number of passages.

Simulation test cases were designed for three harbor modules: a straight channel (Figure 3.10) and two types of bends--regular and truncated (Figure 3.11). All possible buoy stations are indicated in the figures; however, only a subset of these are made available to a particular simulation test case. Table 3.3 presents a summary of the test cases and corresponding situation modifiers. Channel width is 800 ft. for all cases except for Test Case 4D, which assumes a 500 ft. channel. Nominal ship speed is 12 kts for the straight channel cases and 8 kts for bend cases. Runs were made with and without water current, as indicated in the table.

3.4.2 Model Component Analysis

As discussed above, both model component and composite (Monte Carlo) analyses were performed. Component analyses were made of the estimator and decision/control components, respectively. These analyses had separate objectives. The estimator component analysis was conducted in order to calibrate estimator performance with the information obtained from the interview and other data collection activities. Since less information was obtained regarding pilot/helmsman control performance, the decision/control component analysis took the form of a preliminary sensitivity analysis, designed to identify nominal parameter values and provide assessments of the model's sensitivity to these parameters.

The following subsection presents the results of the estimator analysis; i.e., a description of the current estimator performance. The decision/control analysis is presented in Section 3.4.2.2.

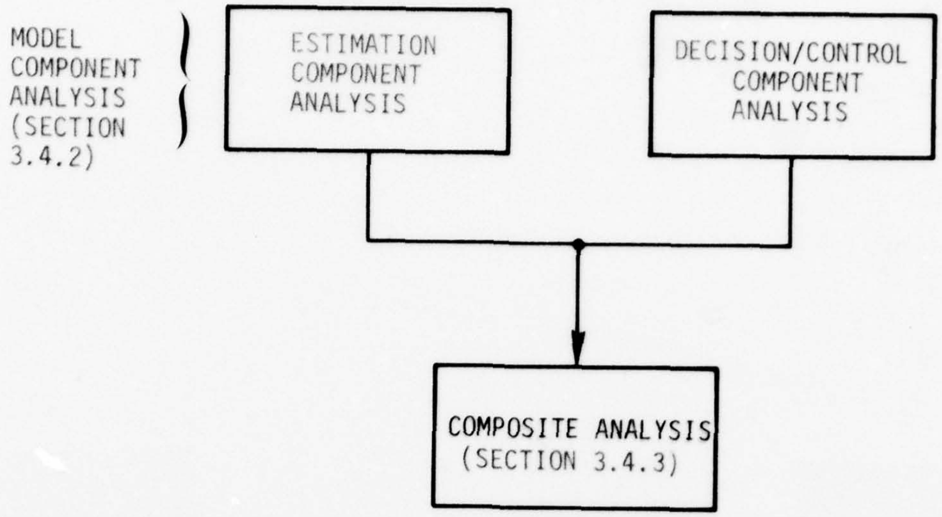


Figure 3.8 Process of Navigation Model Analysis--
Structure of Results Presentation

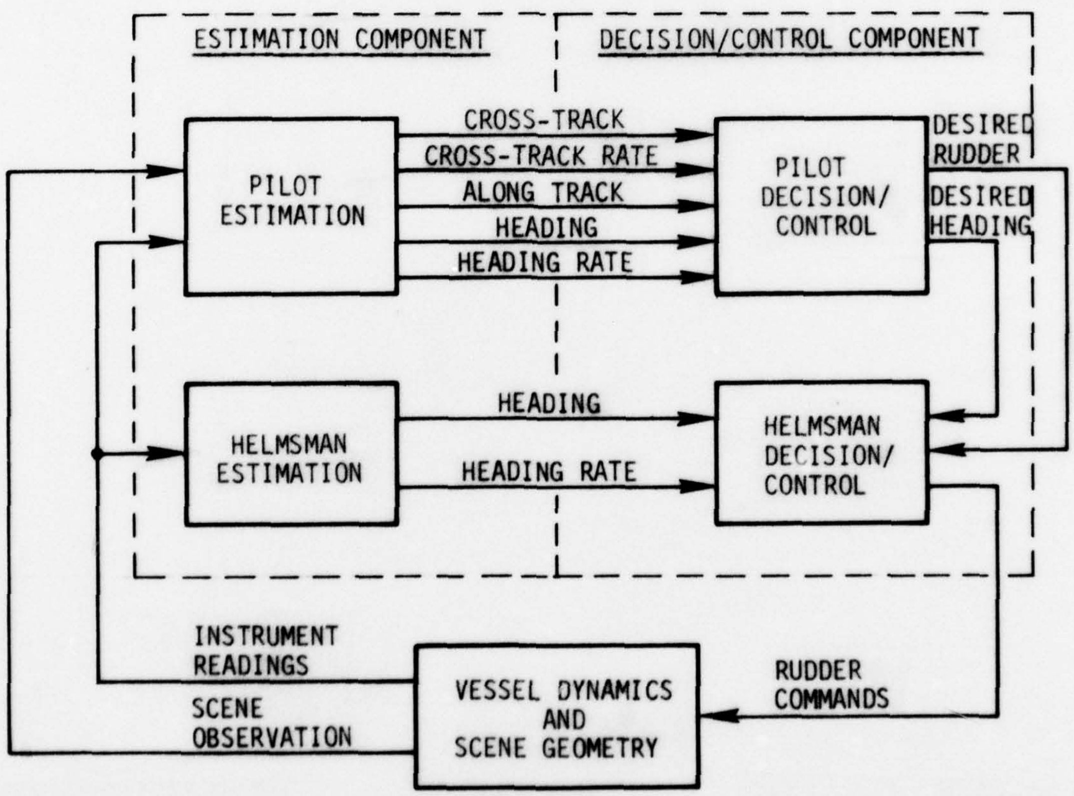


Figure 3.9 Components of the Process of Navigation
Mariner Model

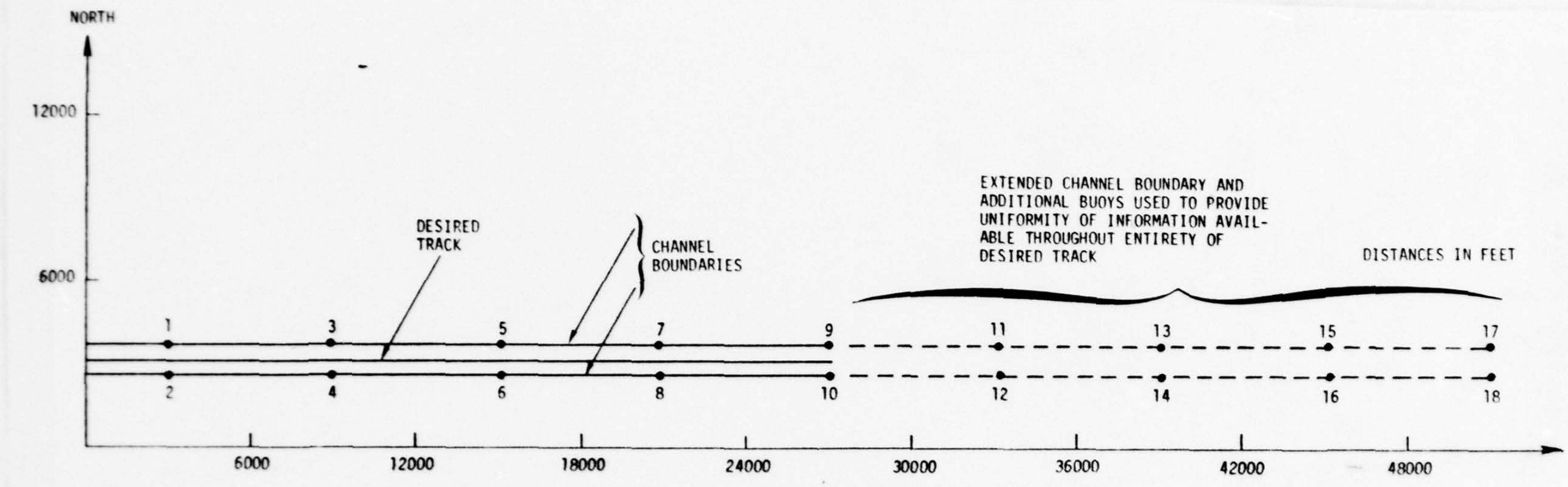


Figure 3.10 Buoy Complement for Straight Channel Test Cases

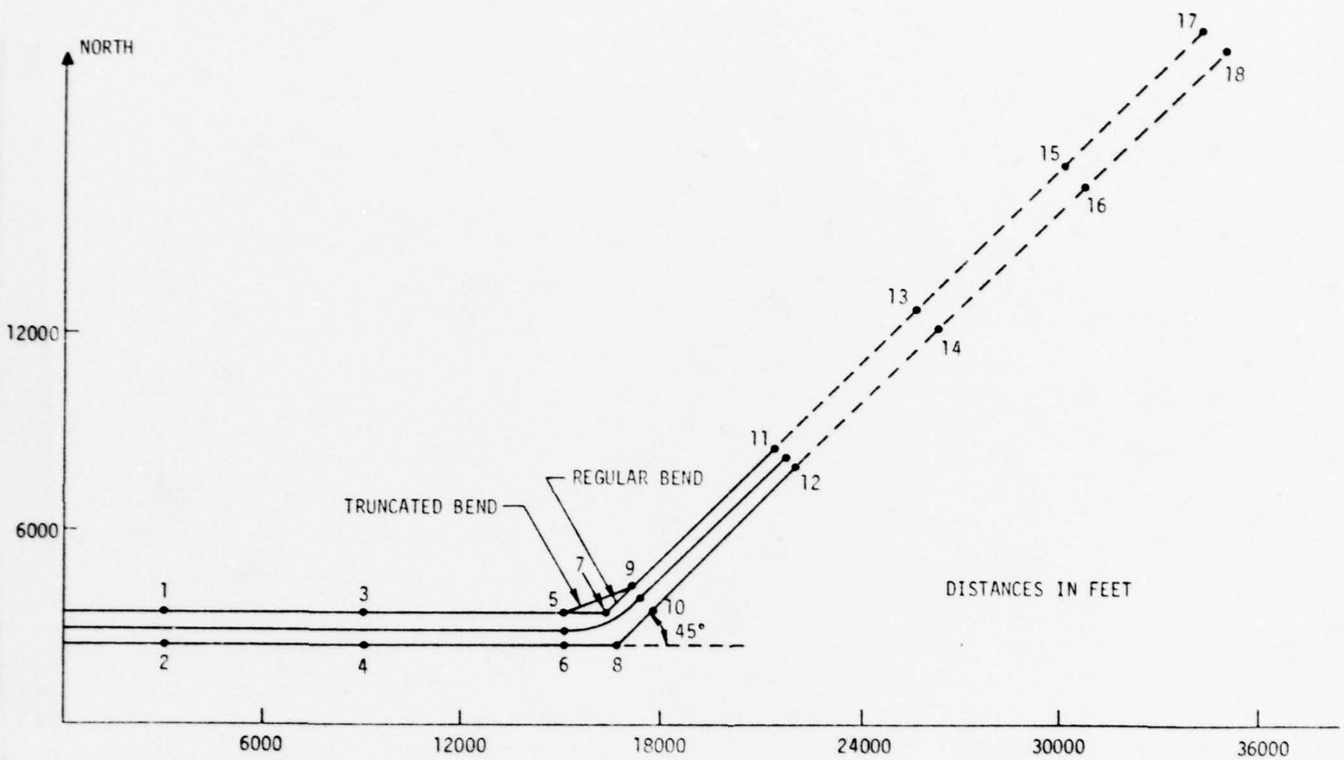


Figure 3.11 Buoy Complement for Channel Bend Test Cases

3.4.2.1 Estimator Component Analysis

The estimator component analysis was conducted in order to identify the estimation error parameter values which produce estimator performance consistent with the interview results, other data collected, and SCI (Vt) project team experience. Preliminary values of mariner observation errors were identified based on related study efforts. Subsequently, variations of the initial values were examined, and estimator performance was scrutinized in terms of which of the available information are used, how they are weighted, when the mariner switches from one primary information source to another, and the resulting vessel position estimation error values.

The test cases for the estimator component analysis (Cases 4A through 4E, Table 3.3) were designed as a mechanism to convey the results of this preliminary calibration effort. For reference purposes, these test cases and the rationale for their inclusion in this phase of the analysis are summarized in Table 3.4.

In all of these cases, the vessel is artificially constrained to stay on the desired track throughout the vessel passage; i.e., the decision/control actions are assumed to be perfect. This is done in order to permit comparative analysis of buoy configurations in a series of single runs, which is possible only when the actual vessel tracks are the same.

In addition to the run descriptions, Table 3.4 also identifies which test cases can be appropriately compared to one another, and the primary purpose of so doing. Each of these comparisons and their results are presented in the following paragraphs. These analyses are limited to consideration of "anticipated" cross-track and along-track estimation errors (standard deviations). These are the primary error statistics of interest, although they cannot, by themselves, be used to accurately predict actual vessel performance (other factors such as the dynamics

Table 3.3

Test Case Descriptions

CASE NO.	TYPE	CHANNEL/ DESIRED TRACK	INITIAL CONDITION	BUOY CONFIGURATION	BUOY NUMBERS AVAILABLE	VESSEL SPEED (KTS)	WATER CURRENT MAGNI-TUDE (KTS)	WATER CURRENT HEAD-ING (KTS)	VISIBILITY
1A	Monte Carlo (10 runs)	Straight/center line	Nominal with crab	Gated configuration: 2-mile spacing	1,2,5,6,9, 10,13,14 17,18	12	1	180	Day, 7 miles
1B	Monte Carlo (10 runs)	Straight/center line	Nominal with crab	Gated configuration: 1-mile spacing	1 thru 14	12	1	180	Day, 7 miles
1C	Monte Carlo (10 runs)	Straight/center line	Nominal with crab	Staggered configuration: 1-mile spacing	1,4,5,8,9 12,13,16	12	1	180	Day, 7 miles
1D	Monte Carlo (10 runs)	Straight/center line	Nominal with crab	Single-side configuration: 1-mile spacing	1,3,5,7,9, 11,13	12	1	180	Day, 7 miles
2A	Monte Carlo (10 runs)	45° truncated bend/center line	Nominal with crab	Gated configuration: 2-mile spacing	1,2,5,6,9, 10,13,14 17,18	8	1	180	Day, 7 miles
2B	Monte Carlo (10 runs)	45° truncated bend/center line	Nominal with crab	Gated configuration: 1-mile spacing	1,2,3,4, 5,6,9,10 11,12,13, 14	8	1	180	Day, 7 miles
2C	Monte Carlo (10 runs)	45° regular bend/center line	Nominal with crab	Gated configuration: 2-mile spacing	1,2,6,7, 8,10,13, 14,17,18	8	1	180	Day, 7 miles
2D	Monte Carlo (10 runs)	45° regular bend/center line	Nominal with crab	Gated configuration: 1-mile spacing	1,2,3,4, 6,7,8,10, 11,12,13, 14	8	1	180	Day, 7 miles

Table 3.3 (Continued)

CASE NO.	TYPE	CHANNEL/ DESIRED TRACK	INITIAL CONDITION	BUOY CONFIGURATION	BUOY NUMBERS AVAILABLE	VESSEL SPEED (KTS)	WATER CURRENT MAGNITUDE (KTS)	WATER CURRENT HEADING (KTS)	VISIBILITY
4A	Single run	Straight/center line	Nominal	Staggered configuration: 1-mile spacing	1,4,5,8, 9,12,13, 16	12	0	0	Day, 7 miles
4B	Single run	Straight/center line	Nominal with crab	Staggered configuration: 1-mile spacing	1,4,5,8, 9,12,13, 16	12	1	180	Day, 7 miles
4C	Single run	Straight/center line	Nominal	Gated configuration: 1-mile spacing	1 thru 14	12	0	0	Day, 7 miles
4D	Single run	Straight/center line 500 ft. channel width	Nominal	Gated configuration: 1-mile spacing	1 thru 14	12	0	0	Day, 7 miles
4E	Single run	Straight/ desired track at left quarter	Nominal	Gated configuration: 1-mile spacing	1 thru 14	12	0	0	Day, 7 miles
5A	Single run	Straight/center line	300 ft. initial cross-track error	Not applicable (N/A)	N/A	12	0	0	Day, 7 miles
5B	Single run	Straight/center line	150 ft. initial cross-track error	N/A	N/A	12	0	0	Day, 7 miles
5C	Single run	Straight/center line	4° initial heading error	N/A	N/A	12	0	0	Day, 7 miles
5D	Single run	Straight/center line	Nominal	N/A	N/A	12	1	180	Day, 7 miles
5E	Single run	45° truncated bend/center line	Nominal	N/A	N/A	8	0	0	Day, 7 miles

Table 3.4

Estimation Component Analysis:
Run Descriptions and Comparisons

CASE NO. (TABLE 3.3)	RUN DESCRIPTION*	COMMENTS
4A	1-mile staggered buoys	Nominal staggered buoy configuration
4B	1-mile staggered buoys, 1-knot cross current	To be compared with Case 4A to evaluate the effect of current on information accuracy.
4C	1-mile gated buoys	Nominal gated buoy configuration; to be compared with Case 4A to establish the extent of additional information afforded by gated buoys.
4D	1-mile gated buoys, 500 ft channel	500 ft channel; to be compared with Case 4C to evaluate the sensitivity of information accuracy to channel width.
4E	1-mile gated buoys, desired track at left quarter	Track at left quarter; to be compared to Case 4C to evaluate the effect of loss of symmetry.

*All runs were with an 800 ft channel width, no current, centerline track; unless otherwise noted.

of the errors, rate estimation accuracy, and vessel and mariner responses must be considered; as they are in the Monte Carlo execution mode).

Test Case 4A vs. 4B

These cases can be compared in order to provide a preliminary evaluation of the effect of current on the accuracy of the information available. Based on the error modeling techniques currently being utilized, the effect of water current was expected

to be negligible for gated configurations. The orientation of vessel is of less significance when gated buoys are available because the mariner need not rely on observations of angles off the bow. As a result, these two test cases were run with a staggered buoy configuration.

The information utilized (i.e., selected by the State Estimator logic, based on minimum anticipated error variances) for cross-track and along-track is shown in Table 3.5.

The along-track uncertainties (standard deviations) were identical. This occurs since the along-track information is obtained primarily from distance observations, which are not sensitive to vessel orientation. A plot showing the results for the no-current case is presented in Figure 3.12.* (Buoy passages in all of the 4-series cases occur at time points 150, 450, 750 and 1050).

The cross-track position uncertainties are presented in Figures 3.13 and 3.14 for the no-current (4A) and current (4B) cases, respectively. These results are virtually identical; however, careful comparison of the plots reveals one item of significance. The no-current case produces a repeatable steady state condition between each buoy, beginning after the initial transients decay (roughly 450 seconds). A somewhat different steady state condition exists for the case with current (4B). Between 150 and 450 seconds and between 750 and 1050 seconds, the primary buoy being used (i.e., the closest) is to the right of the vessel. The current is coming from the left, causing the vessel heading (crab) to be left of track. This increases the angle of the buoy off the bow. The error modeling technique presumes that the mariner's ability to measure (observe) this angle is diminished; his ability to estimate cross-track is therefore also diminished. The reverse

*All figures are located at the end of this subsection to facilitate comparison of results.

Table 3.5

Information Utilized for a 1-Mile Staggered Buoy Configuration

SIMULATION TIME (SECONDS)	CORRESPONDING VESSEL POSITION	SOURCE OF CROSS-TRACK INFORMATION*		SOURCE OF ALONG-TRACK INFORMATION*	
		PRIMARY	SECONDARY	PRIMARY	SECONDARY
460-650	Immediately Past Buoy, Until 2000 feet from Next Buoy	Angles relative to track of next left and right side buoys	Angle between next two buoys on left side, and distance to next left buoy	Distance to next left buoy and angle between next two left buoys	Distance and angle relative to track of the next left buoy
660-690	2000 feet from Buoy, Until 1200 feet from Buoy	Angle between next two left buoys and distance to next left buoy	Angles relative to track of next left and right side buoys		
700-720	1200 feet from Buoy, Until 600 feet from Buoy		Angle between next two right side buoys and distance to next right buoy		
730-740	600 feet from Buoy, Until 200 feet from Buoy		Distance and angle relative to track of next left buoy		
750	Abeam of Buoy	Distance and angle relative to track of left side buoy	Distance to next left buoy, and angle between next two left buoys		Angle relative to track of left side buoy

*Use of left and right side buoys is reversed as each buoy is passed. For the time period illustrated in this table, the closest buoy is on the left side.

is true when the primary buoy being used is to the left (between 450 and 750 seconds).

The impact of this phenomenon is more pronounced in a single sided configuration, as will be seen in the Monte Carlo results. Since this result is not strictly in accord with the interview results and project team experience, the error modeling technique for angles off the bow (angles relative to track) should be re-evaluated.

Test Case 4A vs. 4C

These cases can be compared in order to determine the relative information content of gated buoys in contrast to staggered buoys. In each of these cases, the buoy spacing is 1-mile. The comparison is therefore not addressing which configuration is more cost effective, but merely addresses the difference in the information available.

The along-track uncertainty for the gated configuration (4C) is presented in Figure 3.15. The along-track results for Case 4A were presented in Figure 3.12. The cross-track uncertainties are shown in Figures 3.11 and 3.16 for Cases 4A and 4C, respectively.

In the gated configuration, cross-track information was obtained (by the model) from angle equality between left and right side buoys, except when within 2,000 ft of the gates. In these regions, the distance difference between the buoys was used; the angular difference was secondary. Along-track information was obtained primarily from distance observations except when gates were passed. At these times angles off the bow were used. This is the model's mechanization of the fact that the mariner can fairly accurately identify that he is in between (in line with) the buoys (an automatic result of the line of position orientation/variance logic).

The along-track results are reasonably similar. This implies that the ability to measure distance to one buoy is not

significantly improved when another buoy is added in the same general proximity. As the vessel passes between the buoys, along-track uncertainty is somewhat more noticeably improved in a gated configuration, because the buoys, being on opposite sides, provide a better reference by which to judge when passing takes place.

A marked difference exists in cross-track uncertainty. Error standard deviations are considerably better for the gated configuration both in the gates (due to the ability to evaluate distance differences to the buoys) and in between gates (due to the improved symmetry of the angles).

Test Case 4C vs. 4D

Cases 4C and 4D are identical except for channel width. A 500 ft channel width was utilized in Case 4D, as compared to 800 ft in Case 4C. The cross-track results for the 500 ft channel are presented in Figure 3.17; along-track results are presented in Figure 3.18. The information utilized was virtually the same in Case 4D as in 4C.

In general, the 500 ft channel produces slightly better accuracies. This is as expected; the angles between buoys are smaller, which permits more accurate angle comparisons. Further, distances to the buoys are noticeably smaller when the gates are passed. Logically, these results should not be interpreted to mean that narrower channels are safer; but merely that, at least to some extent, a trade-off between channel width and information accuracy exists.

Test Case 4C vs. 4E

Case 4E is a gated configuration, with the desired track at the left quarter point. In this scenario, the angle and distance symmetry normally associated with gated configurations is perturbed.

The cross-track and along-track uncertainties are presented in Figures 3.19 and 3.20, respectively. In comparison to the centerline case, cross-track uncertainty is greater with the offset track. This is true despite the fact that the vessel passes reasonably close to the left side buoys. Cross-track uncertainty in between the gates is only slightly worse in the offset track case. It is appropriate to note that the information utilized by the mariner model was the same in these two cases. Distance and angle equalities were used; but their accuracy was degraded.

These results imply that the ability to estimate distance differences is markedly better than the ability to estimate distances themselves. This is expected, but the extent to which this is true is not yet firmly established. This is a model validation issue. In this regard, the question to be resolved is: "How close must a vessel/mariner pass by a single buoy in order that his uncertainty be equivalent to exactly splitting an 800 ft wide gate?" Any information obtained pertaining to this question can be readily incorporated into the model merely by altering the relative proportions of bias, common and random observation errors (these error terms and their impact on model performance are described in Appendix D). A similar phenomenon occurs with regard to angles, but to a lesser extent. This, again, is an item for validation.

3.4.2.2 Decision/Control Component Analysis

The objectives of the decision/control component analysis are twofold:

(1) To select appropriate values for mariner decision/control parameters and make preliminary assessments of the model's sensitivity to these parameters; and

(2) To demonstrate representative mariner model response under controlled conditions.

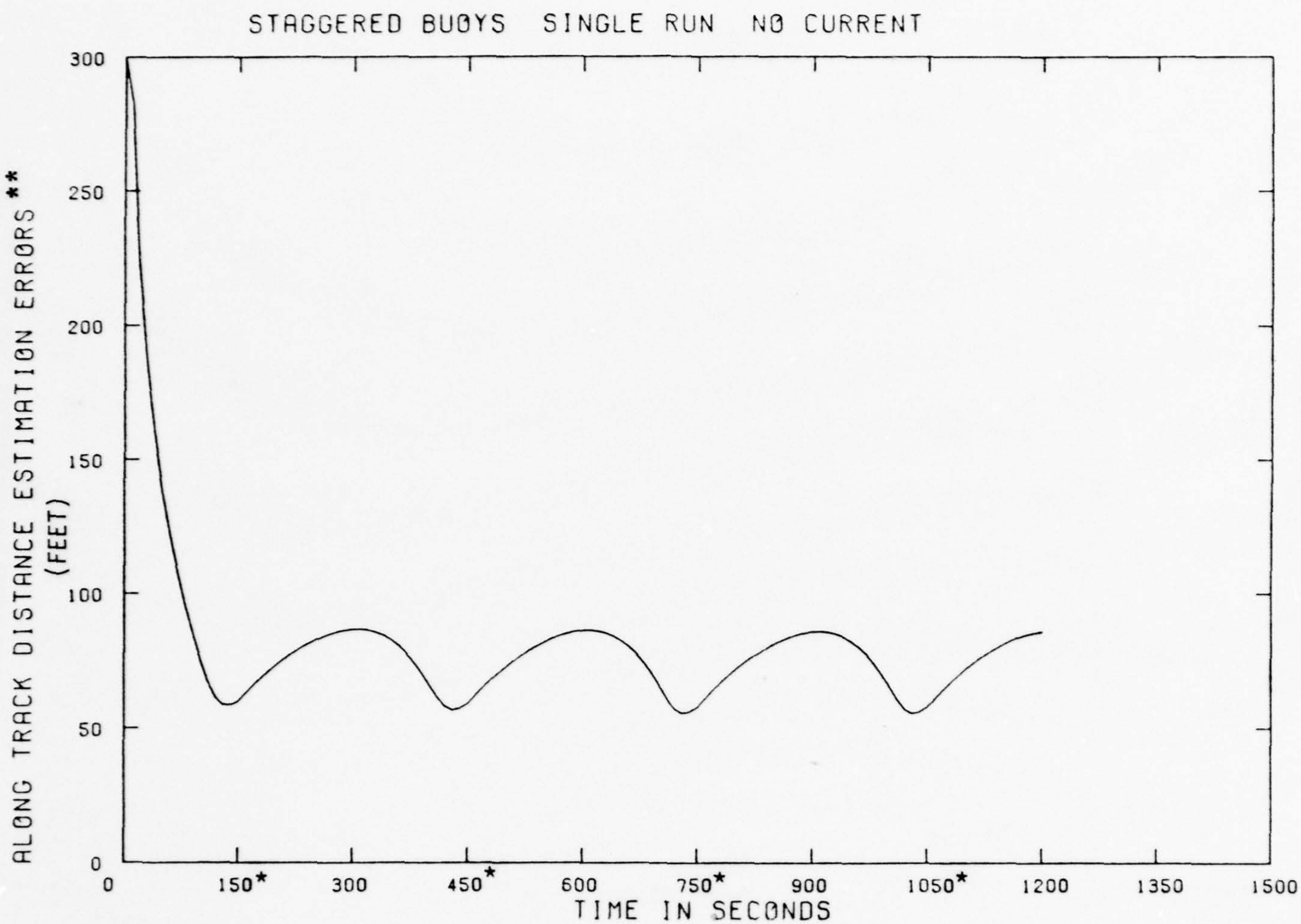


Figure 3.12 Along-Track Uncertainty: Case 4A

*Buoy Passages

**Anticipated Standard Deviation

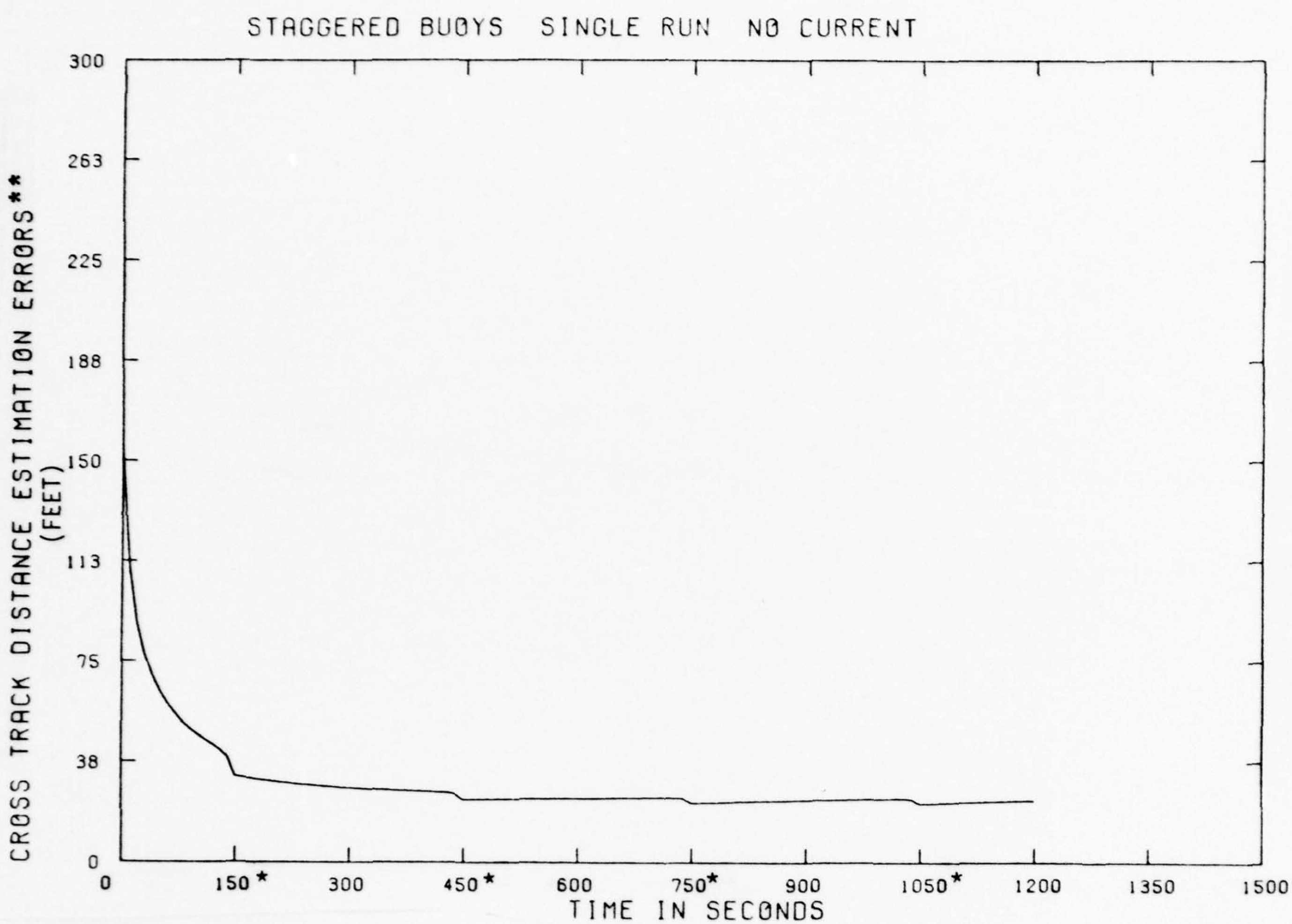


Figure 3.13 Cross-Track Uncertainty: Case 4A

*Buoy Passages

**Anticipated Standard Deviation

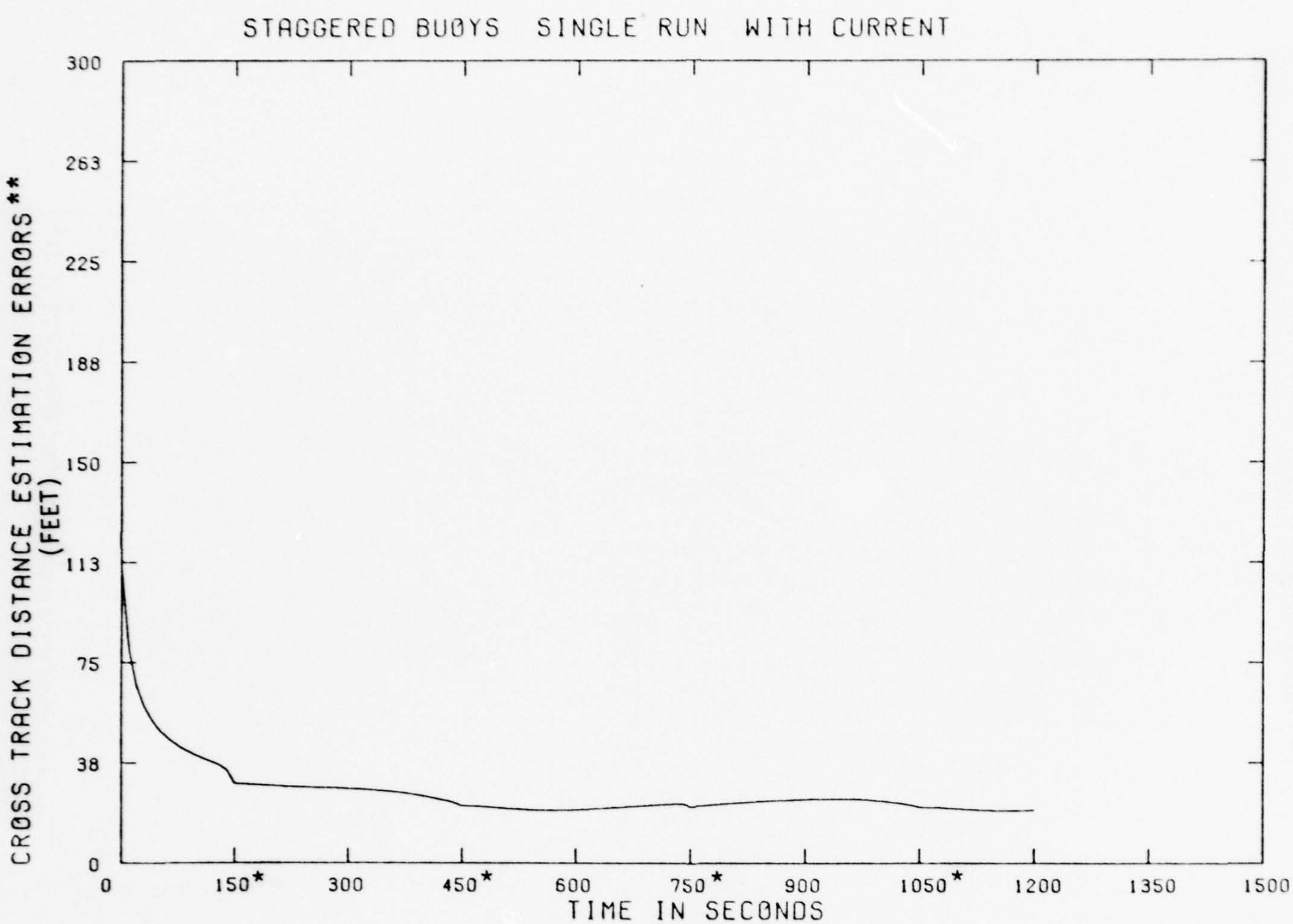


Figure 3.14 Cross-Track Uncertainty: Case 4B

*Buoy Passages

**Anticipated Standard Deviation

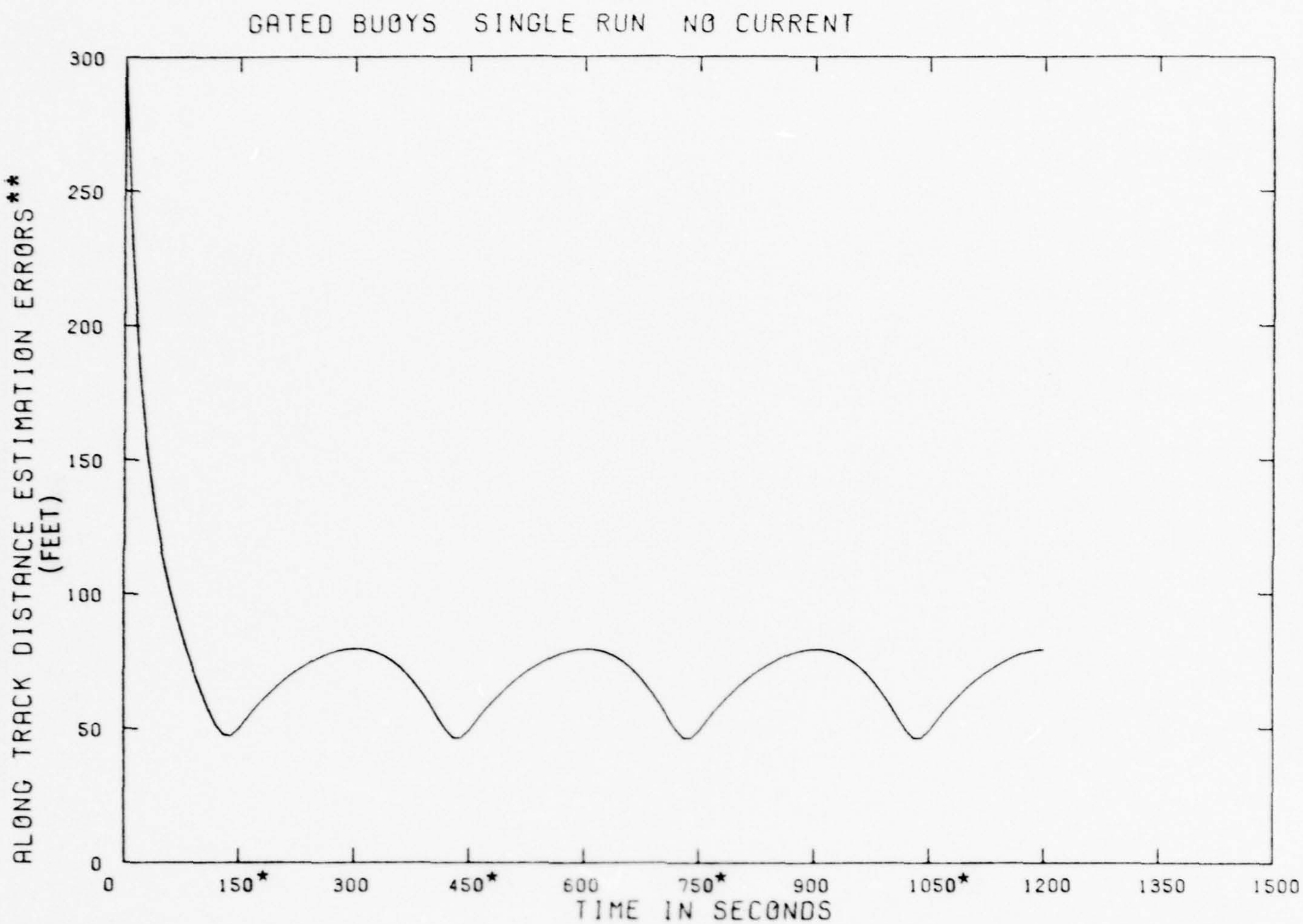


Figure 3.15 Along-Track Uncertainty: Case 4C

*Buoy Passages

**Anticipated Standard Deviation

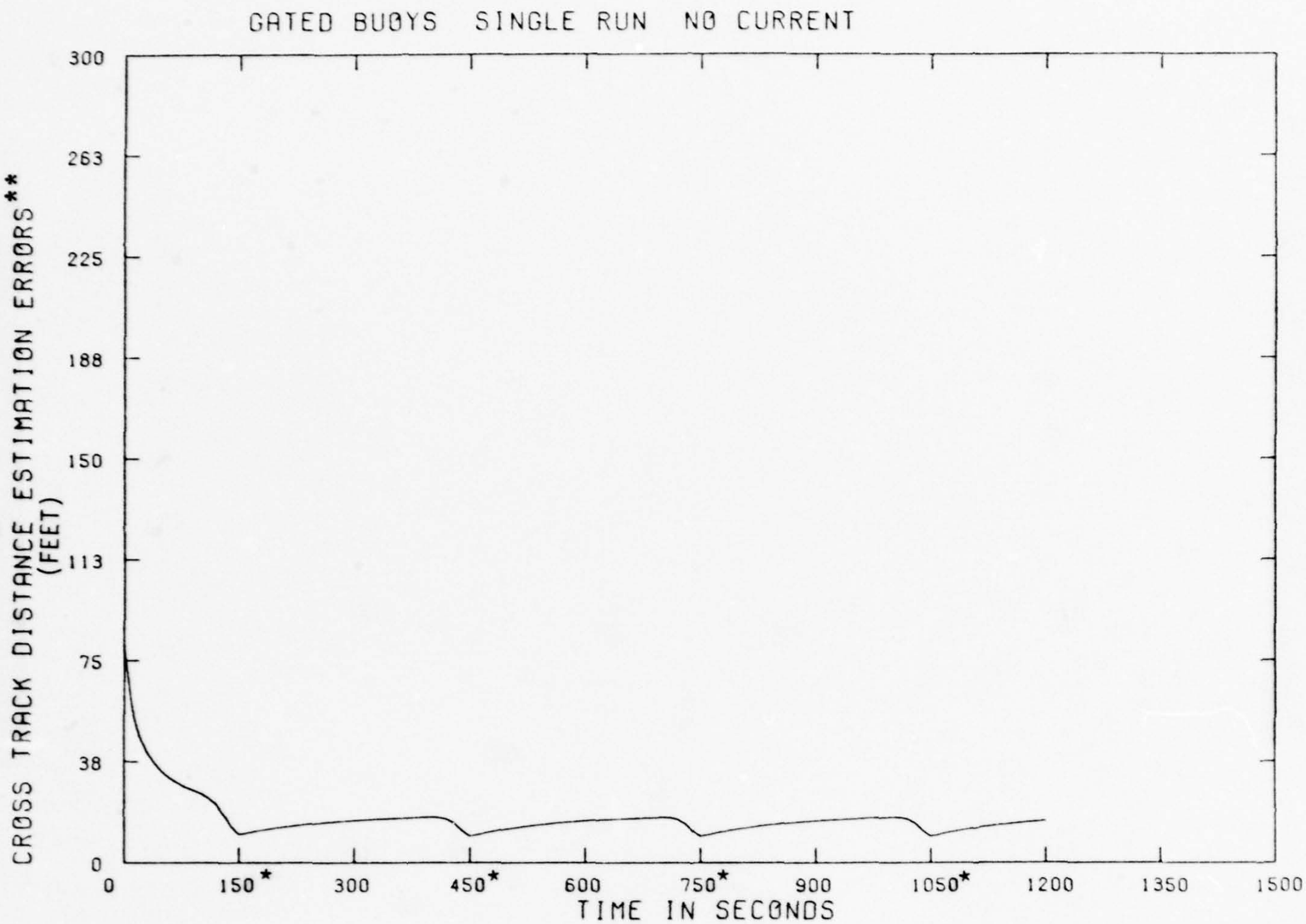
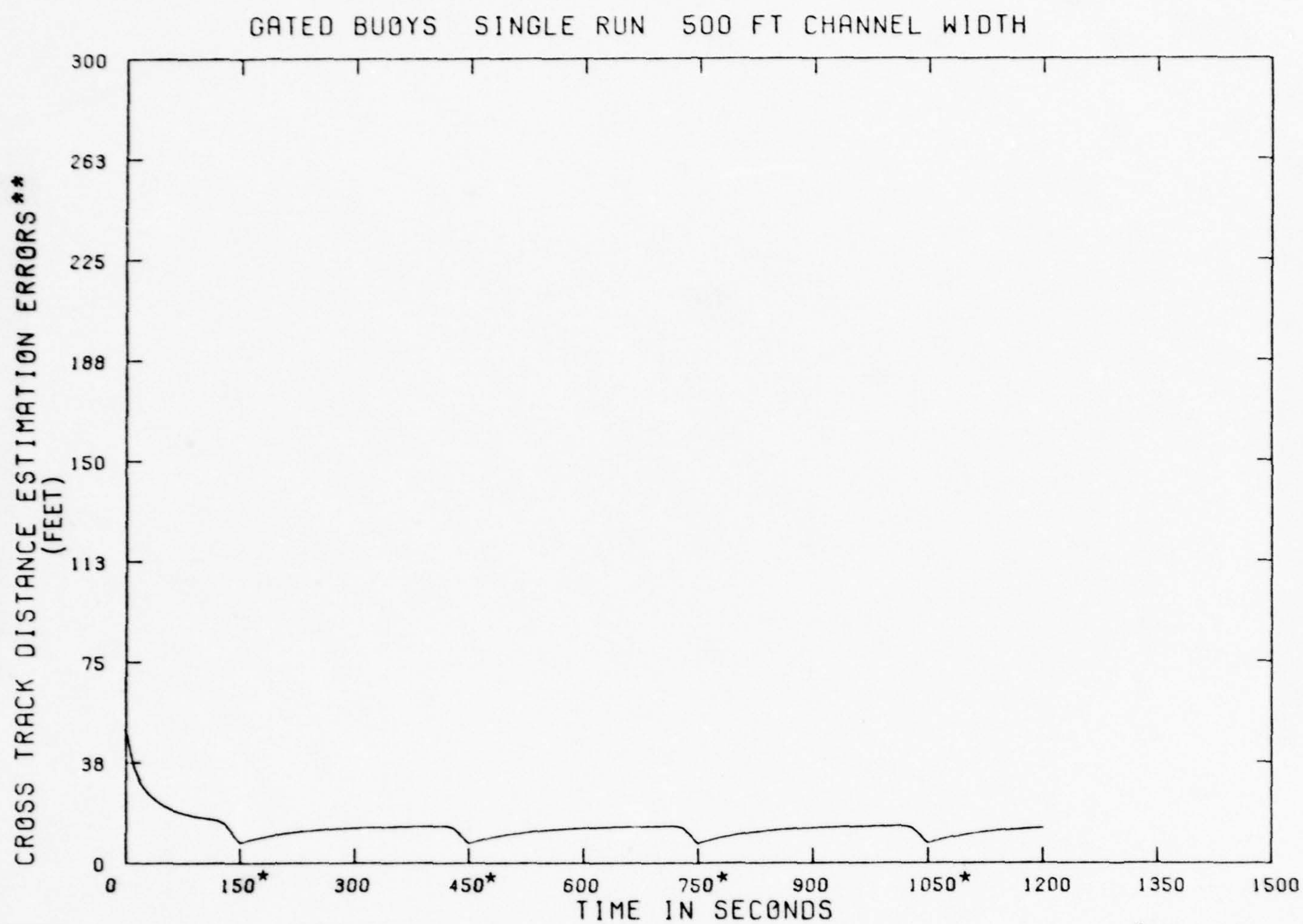


Figure 3.16 Cross-Track Uncertainty: Case 4C

*Buoy Passages

**Anticipated Standard Deviation



*Buoy Passages

**Anticipated Standard Deviation

Figure 3.17 Cross-Track Uncertainty: Case 4D

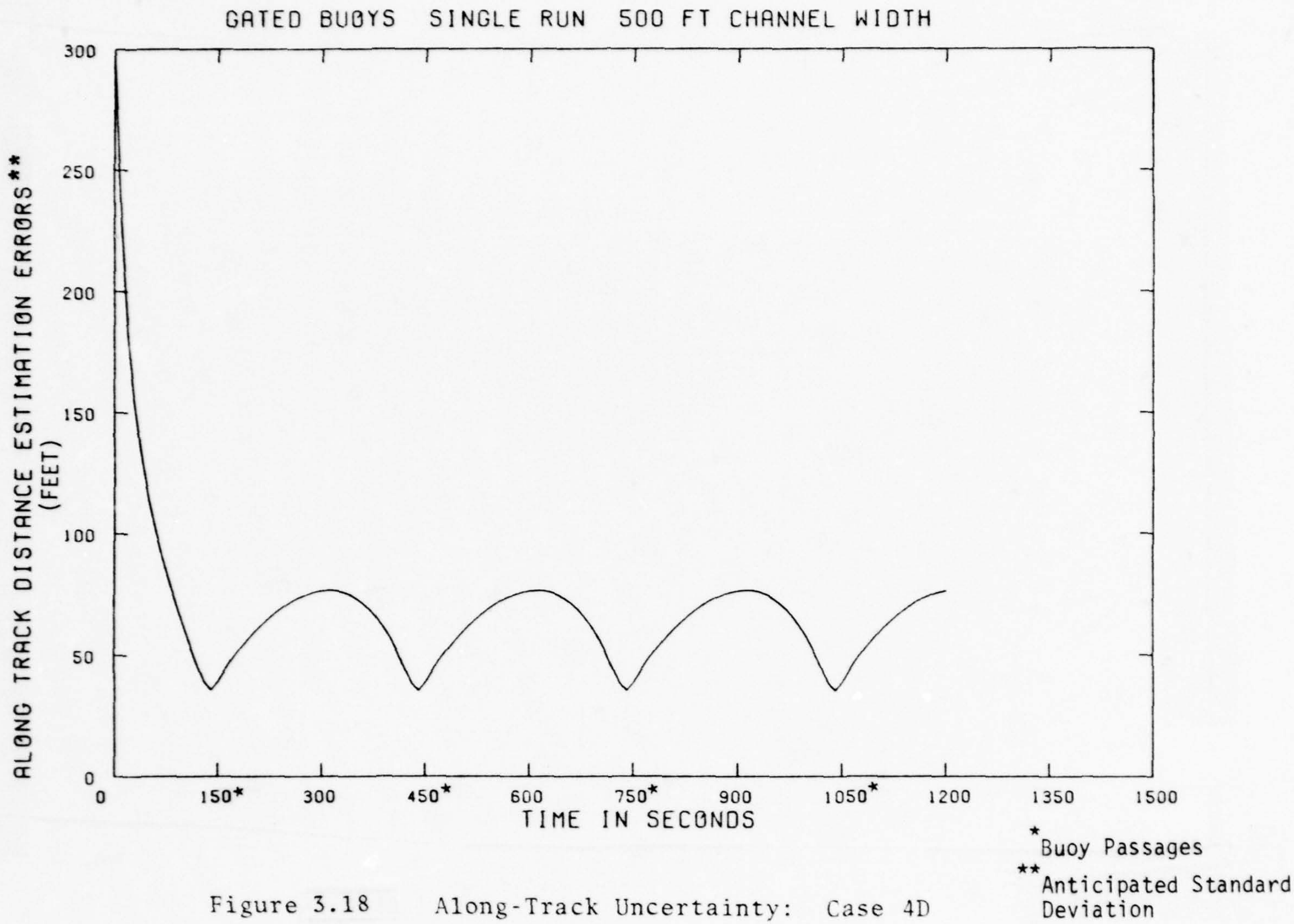


Figure 3.18 Along-Track Uncertainty: Case 4D

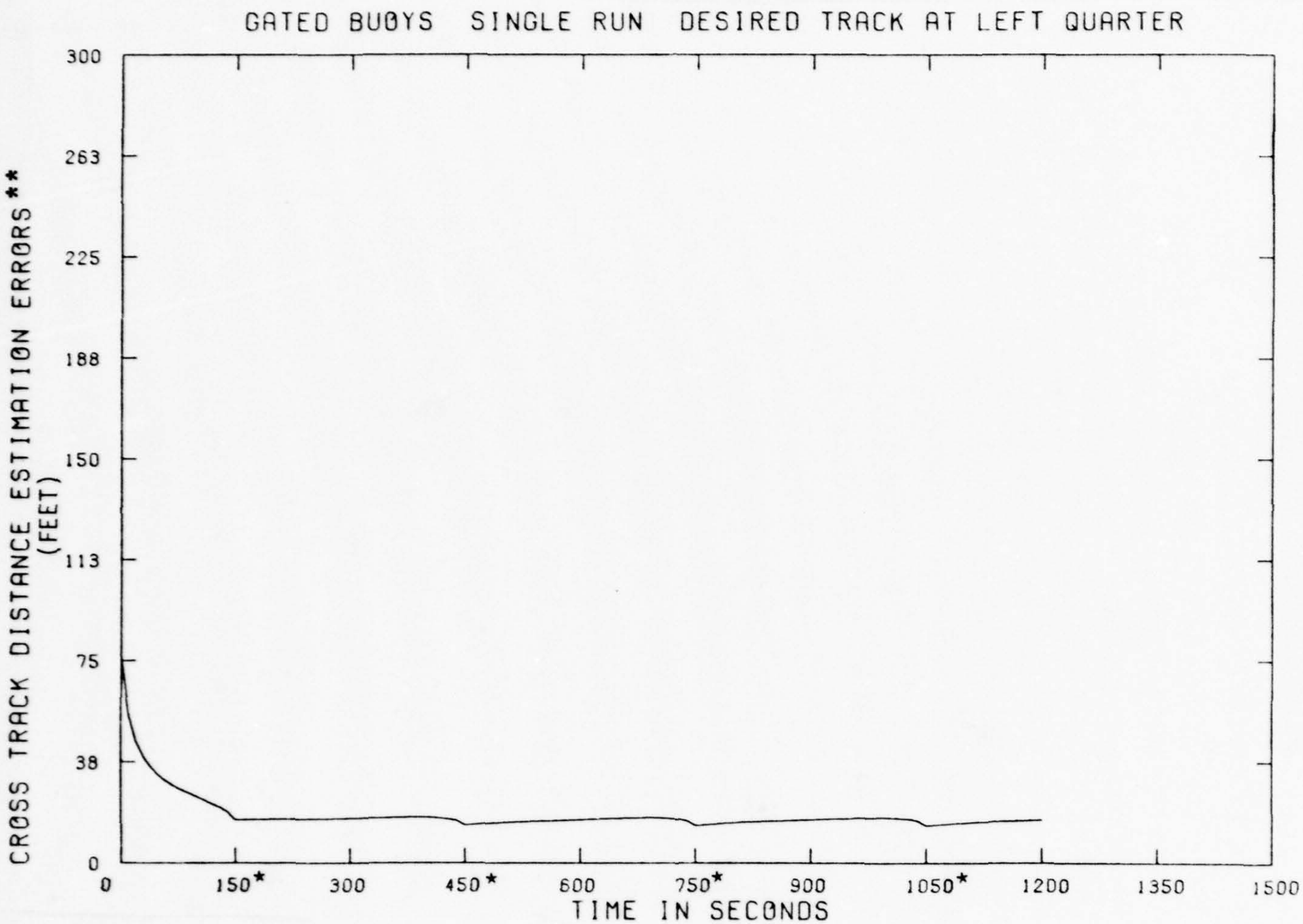


Figure 3.19 Cross-Track Uncertainty: Case 4E

*Buoy Passages

**Anticipated Standard Deviation

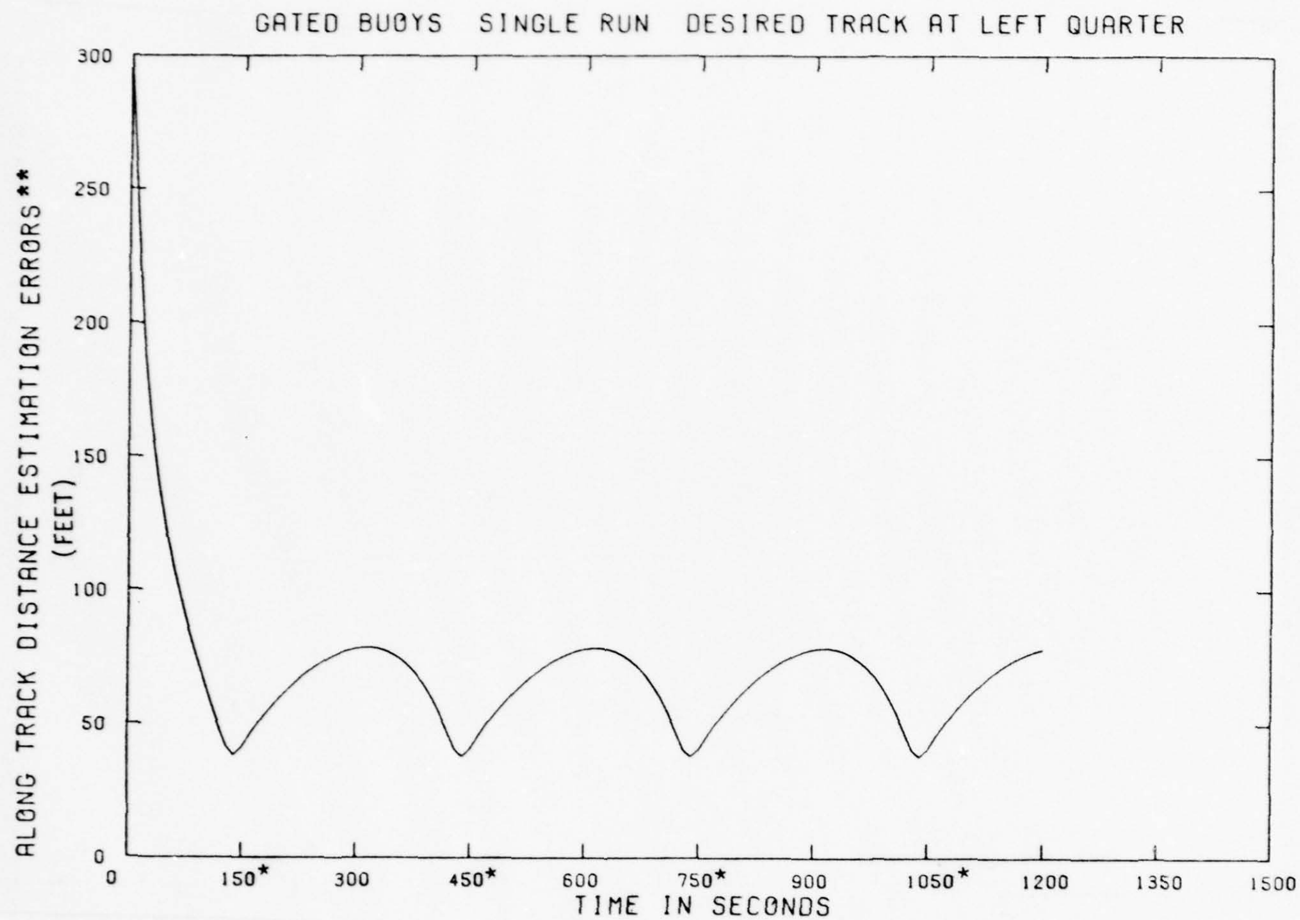


Figure 3.20 Along-Track Uncertainty: Case 4E

*Buoy Passages
**Anticipated Standard Deviation

The first objective is accomplished through a combination of linear control system analysis and nonlinear offline simulation. The results of these offline studies are reported in Appendix H, "Decision/Control Parameter Selection and Sensitivity", and summarized in Table 3.6. In support of the second objective, the remainder of this section presents a demonstration of representative model performance using the nominal parameter values listed in the table.

Decision/control performance under a variety of conditions is demonstrated by Runs 5A through 5E as defined in Table 3.3. For reference, these test cases and the rationale for their inclusion in this phase of the analysis are summarized in Table 3.7. In all of these test cases, the mariner acts upon the actual (rather than estimated) vessel state; i.e. the estimation function is assumed to be perfect. In this way, the decision/control process can be examined independently of buoy placement and estimator performance.

Runs 5A through 5D exercise the multi-region return-to-track and track-keeping control laws for a variety of initial conditions. For reference, these decision regions and their respective control laws are shown in Figure 3.21. The numerical values of the threshold parameters and feedback gains which correspond to the test cases are presented in Table 3.6.

It is appropriate to note that, within the current version of the Process of Navigation model, the indifference regions (thresholds) do not vary dynamically. They are based upon parameters which are changable by the user, but they are not changed within the model as a function of such factors as channel width, bend negotiation, information available, vessel position, etc. Within Phase II, continued effort will be devoted toward identifying the sizes of the indifference regions, and also toward establishing if they vary dynamically, to what extent and under what circumstances.

Run 5A begins with a large cross-track deviation (300 ft) so that the pilot will initially apply the Region #3 control

Table 3.6

Pilot/Helmsman Decision and Control Parameters

PROGRAM NAME	DESCRIPTION	APPROXIMATE EXPRESSION	NUMERICAL VALUES USED 8 kts	12 kts	COMMENTS
Decision Threshold Parameters					
PDB1	Pilot cross-track deviation threshold--level 1 (linear cross-track feedback law).	1/4 (W/2)	100 ft.	100 ft.	Threshold based on projected cross-track KTC seconds into the future.
PDB2	Pilot cross-track deviation threshold--level 2 (return to track at desired intercept angle)	1/2 (W/2)	200 ft.	200 ft.	Threshold based on projected cross-track KTC seconds into future. Law used for return to track from large deviations.
KTC	Pilot cross-track preview (prediction) parameter--levels 1 and 2	2 L/U	120 sec.	80 sec.	Projected cross-track ($\widehat{CTD}$) (= CTD + KTC · $\dot{CTD}$) is compared to threshold PDB1 and PDB2.
HDBP	Pilot heading error threshold	2 deg	2 deg.	2 deg.	Threshold based on projected heading error KTHP seconds into the future.
KTHP	Pilot heading error preview (prediction) parameter	2 L/U	120 sec.	80 sec.	Projected heading error (= $\hat{H}$ + KTHP · $\dot{\hat{H}}$) is compared to threshold HDBP.
HDBH	Helmsman steering (heading error) decision threshold	0.5 deg	0.5 deg.	0.5 deg.	Similar to pilot's parameter HDBP
KTHH	Helmsman heading error preview (prediction) parameter	60 sec	60 sec.	60 sec.	Similar to pilot's parameter KTHP
TWAIT	Amount of time pilot waits after achieving benign state before turning course steering control back over to helmsman	30 sec	30 sec.	30 sec	Pilot also supplies desired heading angle to helmsman

Table 3.6 (Continued)

PROGRAM NAME	DESCRIPTION	APPROXIMATE EXPRESSION	NUMERICAL VALUES USED		COMMENTS
			8 kts	12 kts	
Control/Steering Law Gains					
GPHD	Pilot level 1 (Decision Region 2) return-to-track control law gains:	1.2 L/U	68.29	45.78	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GPH		.02 GPHD	1.374	0.9156	
GPCTD	δ_D=GPCTD$\cdot\dot{CTD}$+GPH$\cdot\hat{H}_e$+GPHD $\dot{\hat{H}}_e$	.00015625 x GPHD/U	.000805	.000358	
GPHD	Pilot level 2 (Decision Region 3) and steering law gains:	1.2 L/U	1.374	.9156	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GPH	δ_D=GPH $(\hat{H}_e-H_I)$+GPHD$\cdot\dot{\hat{H}}_e$	.02 GPHD	.000805	.000358	
GHH	Helmsman steering law gains:	0.75 L/U	42.93	28.61	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GHHD	δ_D=GHH$\cdot H_e$+GHHD$\cdot\dot{\hat{H}}$	.0333 GHHD	1.43	.9528	
H_I	Desired track intercept angle for pilot	constant	5°	5°	Currently assumed constant. This will be updated as appropriate in Phase II.
H_E	Heading error	$\hat{H}-H_D$	variable	variable	Actual vessel heading ("compass reading," not direction of travel) minus desired heading. The desired heading is determined by the pilot model as a function of track orientation and crab angle.

W = channel width
U = Ship speed
L = Ship length

Table 3.7

Decision/Control Component Analysis: Run Descriptions

CASE NO. (TABLE 4.3-1)	RUN DESCRIPTION	COMMENTS
5A	Straight channel, 300 ft. initial cross-track error, no current	Exercises the large maneuver (Region 3) control law, returning to track at a 4 deg intercept angle
5B	Straight channel, 150 ft. initial cross-track error, no current	Exercises the normal return to track control law (Region 2)
5C	Straight channel, 4 degree initial heading error, no current	Exercises the normal return to track (Region 2) and steering control laws (Region 1) under adverse heading initial condition.
5D	Straight channel, 4 degree initial heading error, with current	Repeat of 5C with current
5E	Truncated 45 degree bend, nominal initial conditions, no current	Should yield a nearly ideal turn response.

DEC. REGION	CONTROL LAW	CONTROL OBJECTIVE
#1	$R_D = K_H \cdot \hat{H}_e + K_{\dot{H}} \cdot \hat{\dot{H}}_e$	STEER TO DESIRED HEADING
#2	$R_D = K_H \cdot \hat{H}_e + K_{\dot{H}} \cdot \hat{\dot{H}}_e + K_{CTD} \cdot \hat{CTD}$	RETURN TO TRACK
#3	$R_D = K_H \cdot (\hat{H}_e - H_I) + K_{\dot{H}} \cdot \hat{\dot{H}}_e$	RETURN TO TRACK BY STEERING TO INTERCEPT TRACK AT ANGLE H_I

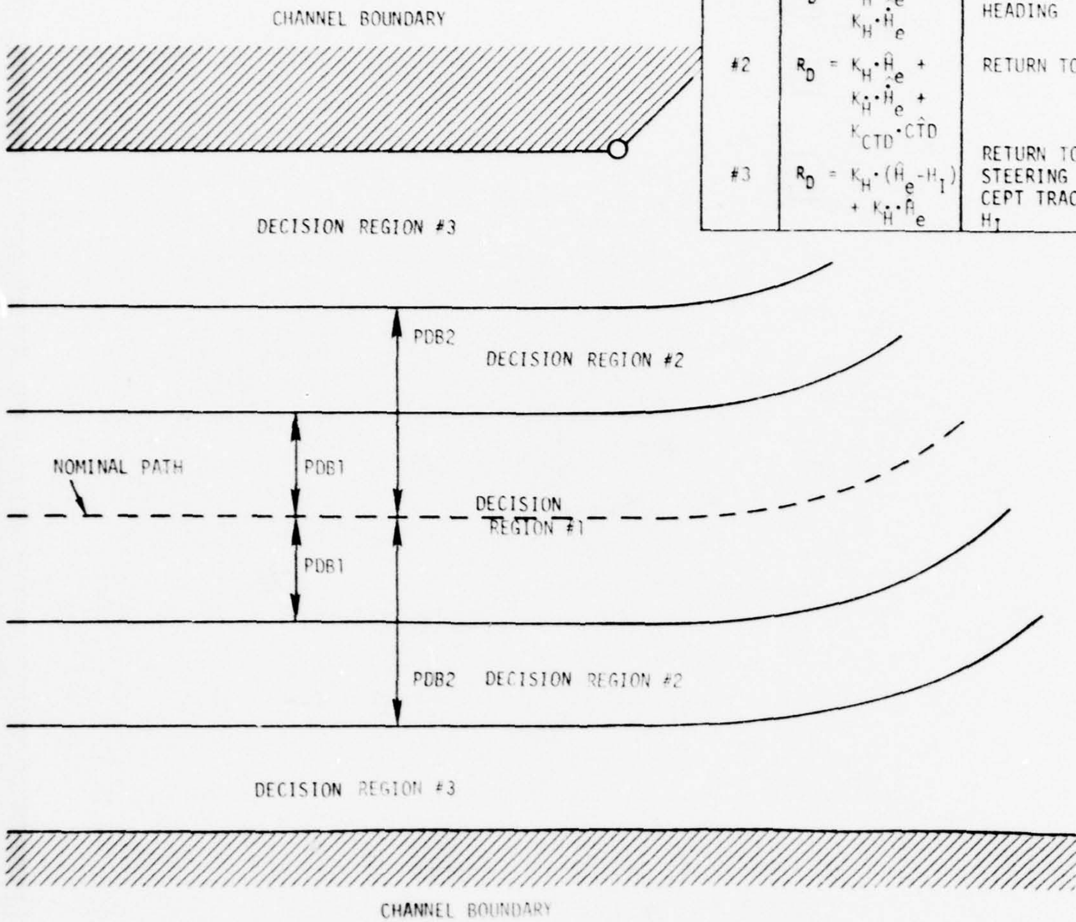


Figure 3.21 Mariner Model Decision Regions and Control Laws

strategy--return to track at a nominal intercept angle (in this case, 5 degrees). The resulting helmsman rudder command, cross-track deviation, and heading error time histories are shown in Figures 3.22-3.24. The quantization level of 5 degrees is clearly shown in the rudder command trace; those commands which are not multiples of 5 degrees are attributed to the helmsman's course steering.* The pilot gives a 5° right rudder command followed at TIME = 100 seconds by 5° left rudder to null heading rate and maintain the desired 5° heading error for track intercept. At TIME = 200 seconds, the pilot detects the projected cross-track to be within Region #1 and reverts to the steering control law, which issues a 5° left rudder command with the objective of nulling the heading error. When the pilot projects heading error to enter the Region #1 steering threshold, he issues a pair of right rudder commands at TIME = 320 and 370 to kill the heading rate. After achieving tolerable heading and heading rate conditions, the pilot turns control over to the helmsman for more precise course steering.

Commanding two pulses instead of one to kill heading rate is attributed to a "chattering" effect of the 5° quantization deadband. Such quantization effects are an idiosyncrasy of the model mechanization, and are not strictly characteristic of the way a human pilot would perform; however, such effects should not appreciably affect statistical model application results. Chattering may be eliminated by utilizing a more complex logic to implement the quantization of pilot rudder commands; such logic will be considered for Phase II model extension.

Run 5B begins with a 150 ft cross-track deviation, which engages the Region #2 control strategy--the resulting helmsman rudder command, cross-track and heading error time histories are shown in Figures 3.25-3.27. The pilot gives a 5° initial rudder

*The helmsman model applies infinitely variable control, but only if the tracking deadband of 0.5 degree heading is exceeded.

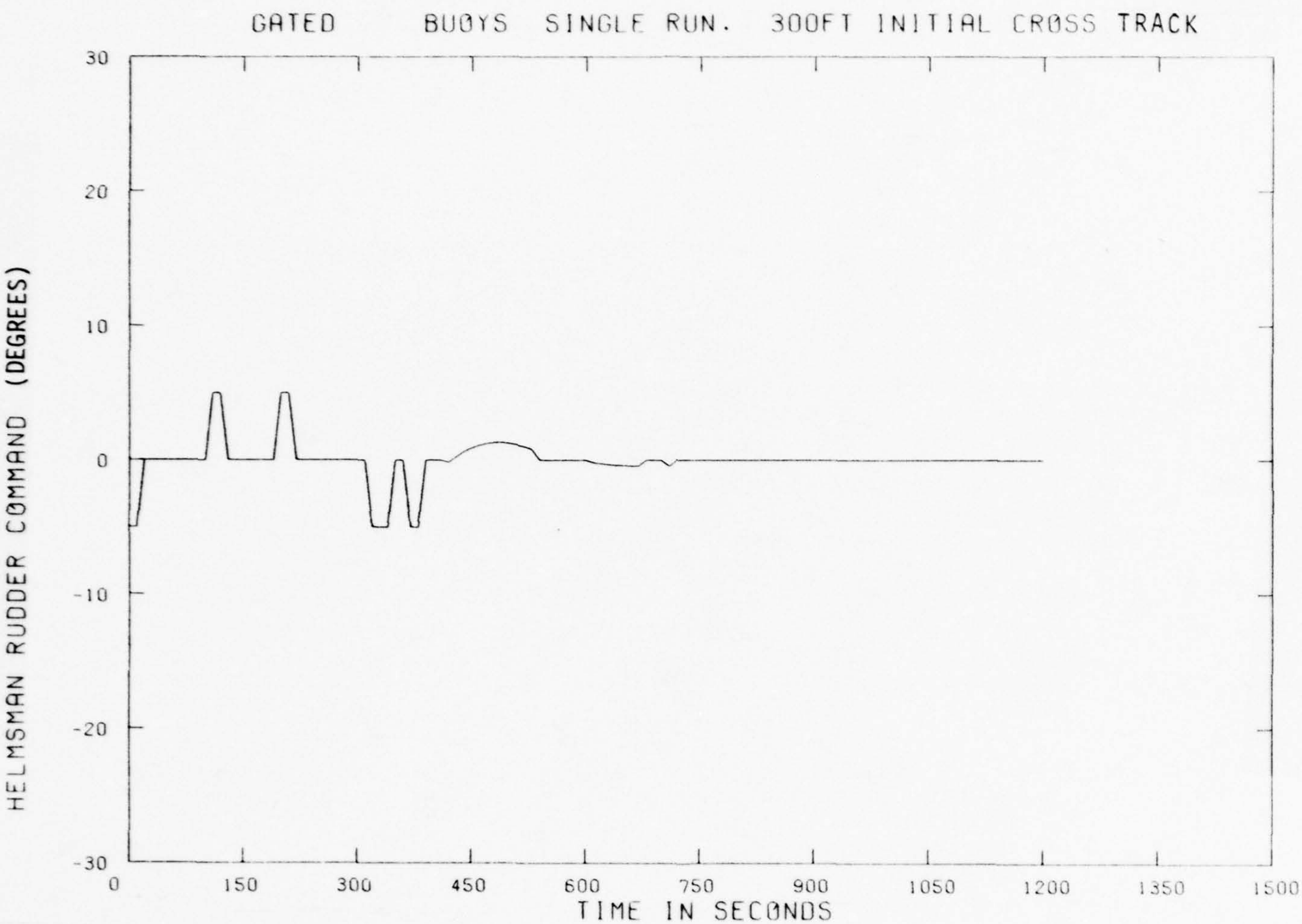


Figure 3.22 Helmsman Rudder Command, Run 5A

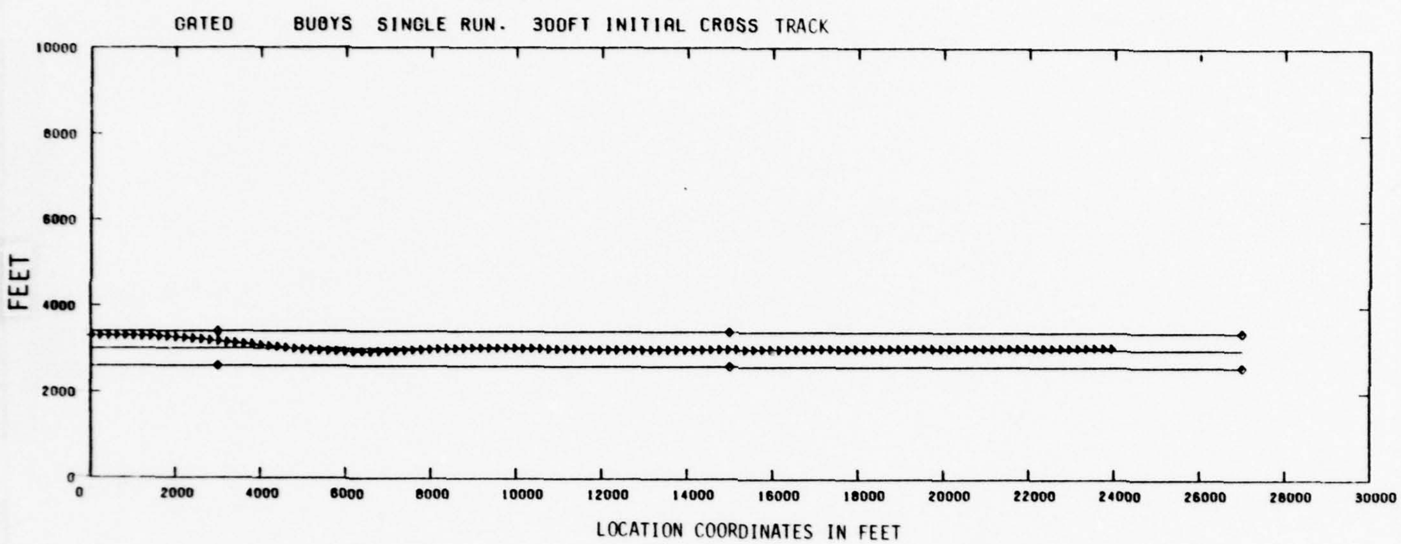


Figure 3.23 Cross-Track Deviation, Run 5A

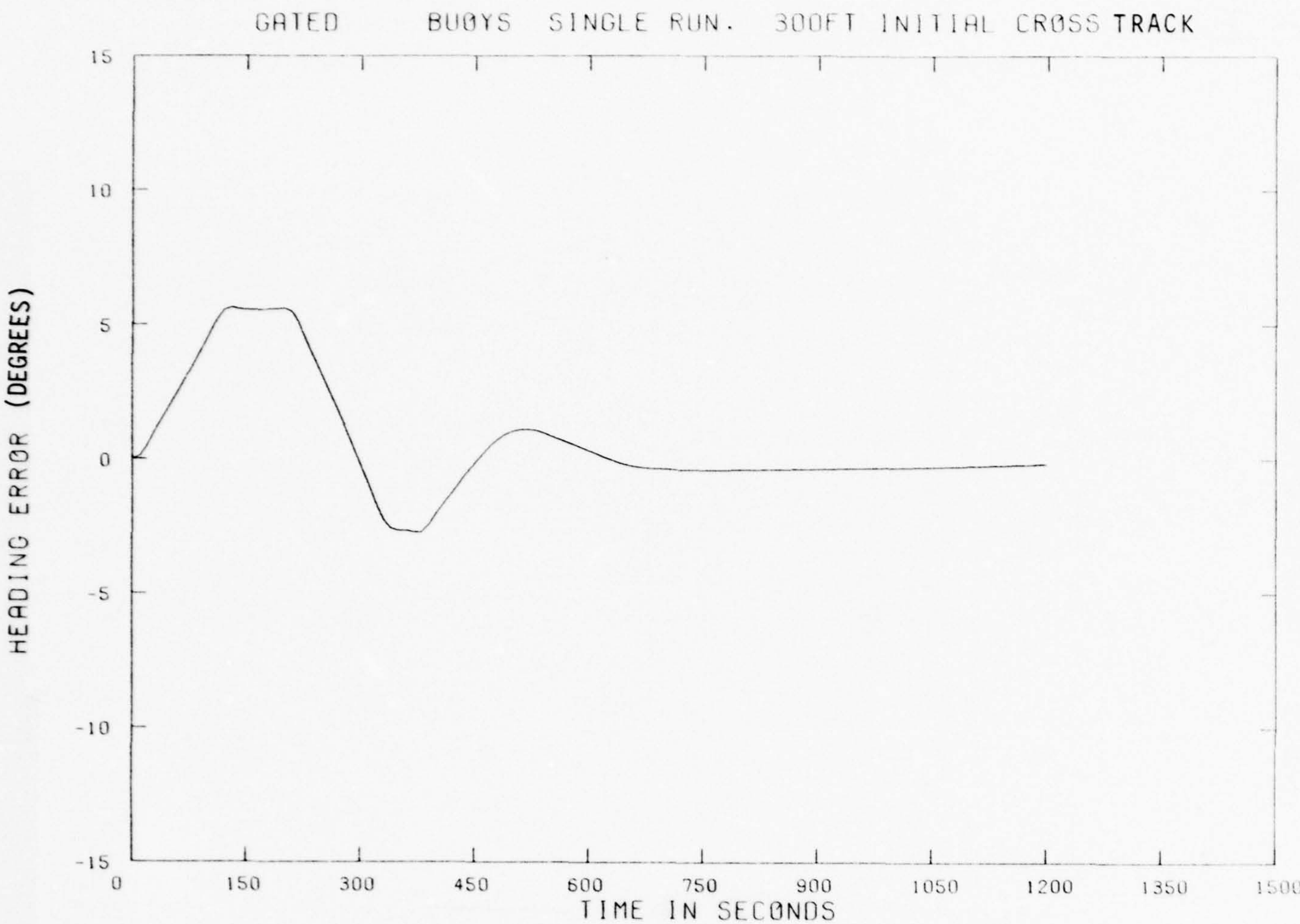


Figure 3.24 Heading Error, Run 5A

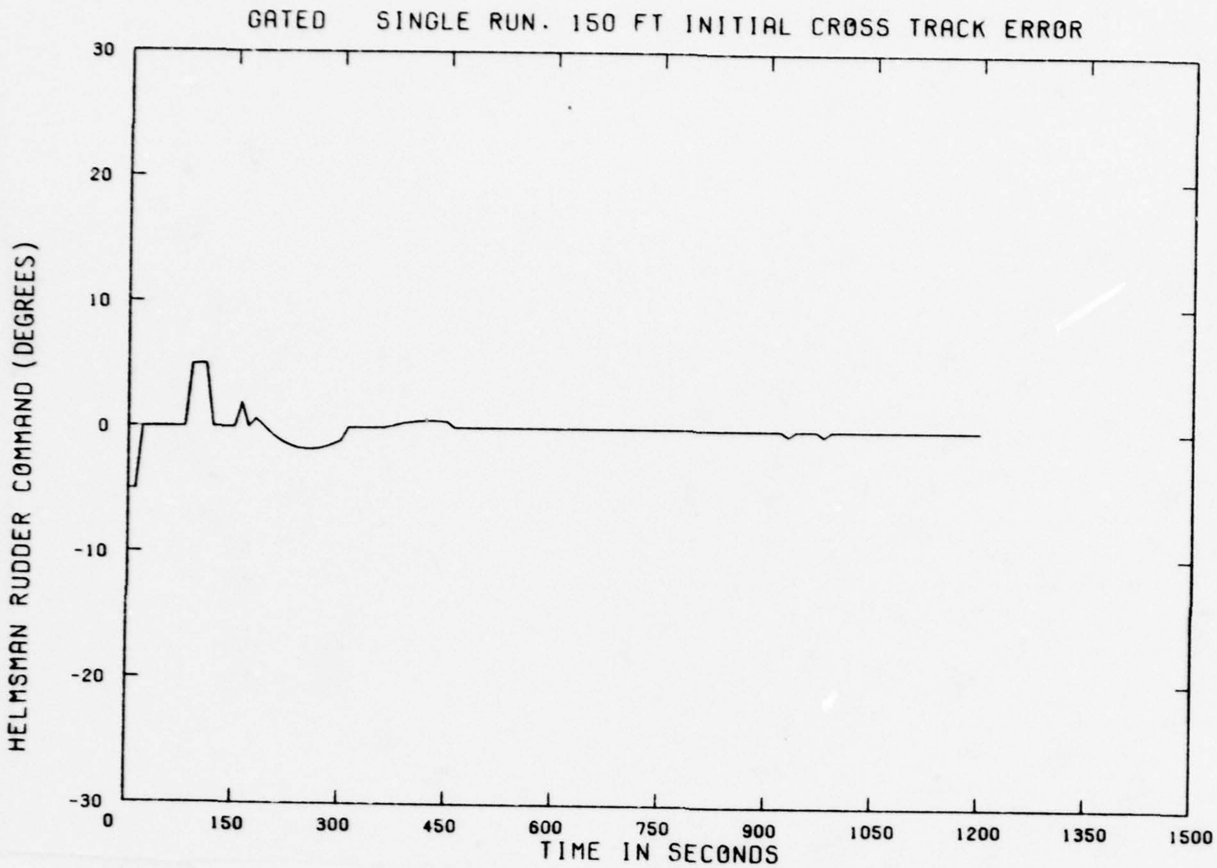


Figure 3.25 Helmsman Rudder Command, Run 5B

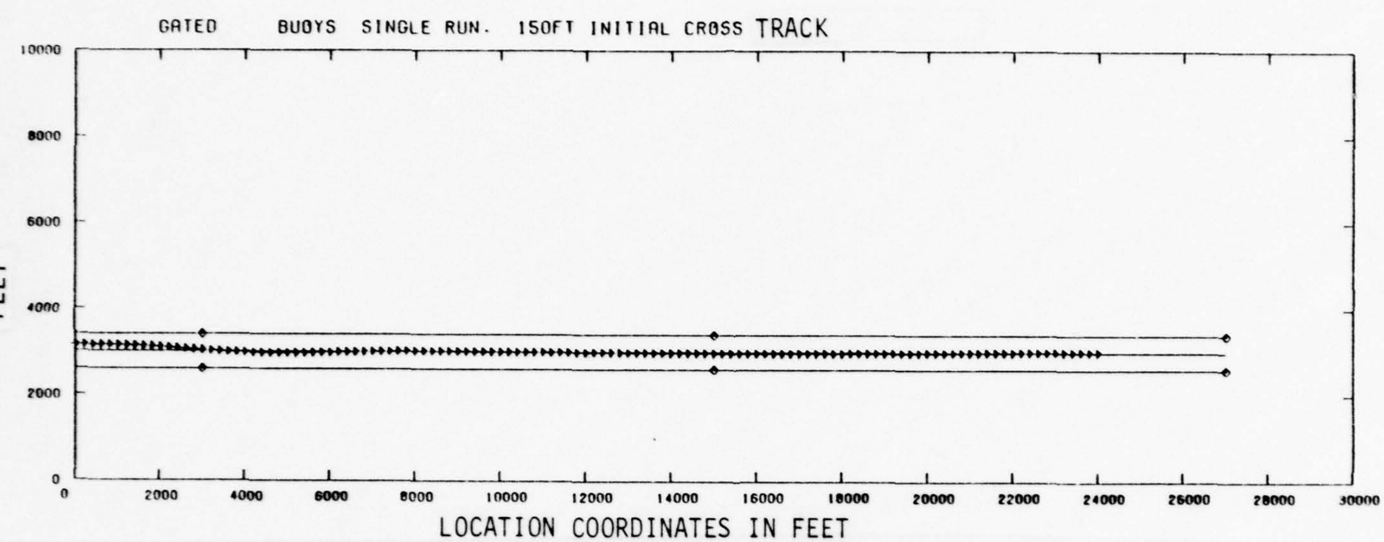


Figure 3.26 Cross-Track Deviation, Run 5B

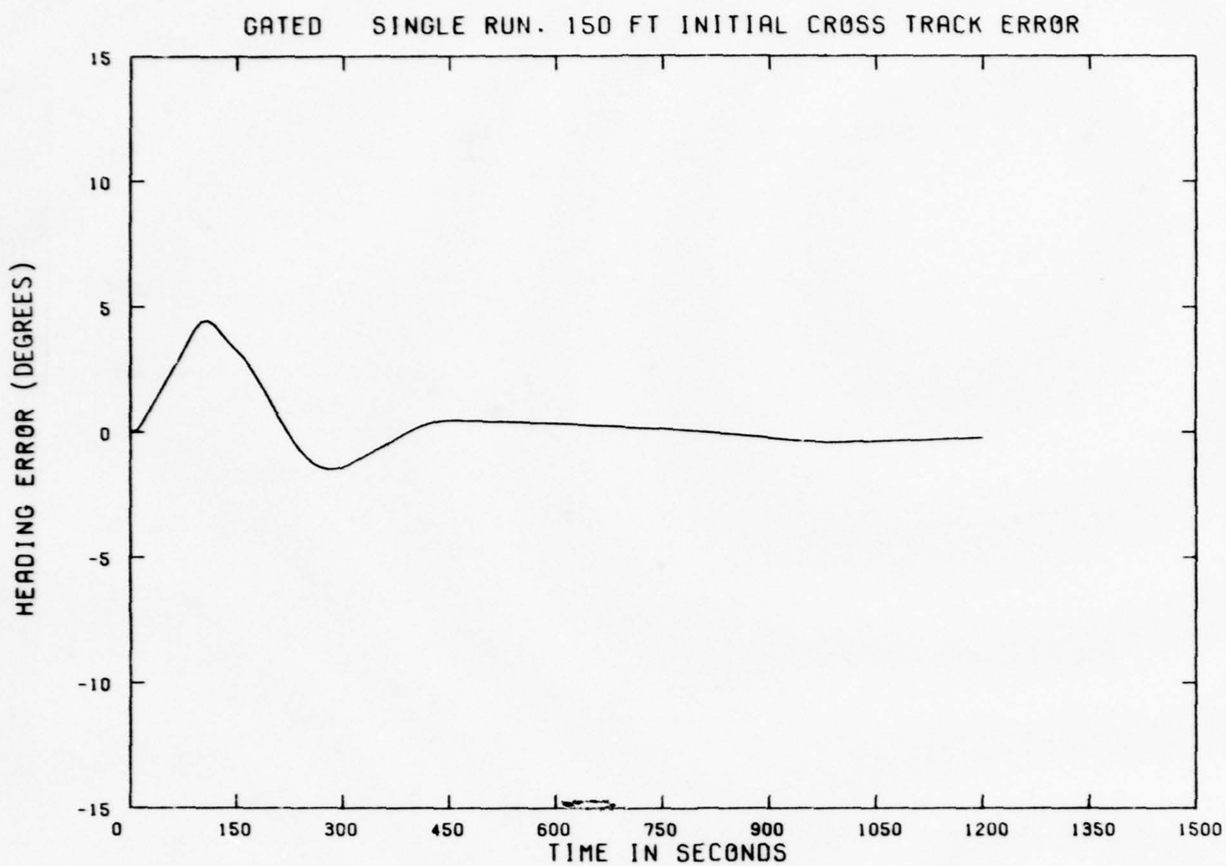


Figure 3.27 Heading Error, Run 5B

command, held for 20 seconds, to head back towards track. At TIME = 90 seconds, he detects that his projected cross-track will be inside the Region #1 threshold and reverts to the steering law, which calls for a 5° left rudder to null heading rate. This action achieves a heading/heading rate combination which is within tolerance, and he again turns control over to the helmsman for precise course steering.

Runs 5C and 5D begin with a 4° initial heading error; the test conditions are identical except that run 5D includes a 1 kt cross current (left to right), which is compensated by a crab angle of 4.78°. Figures 3.28-3.33 present the rudder command, cross-track and heading errors for the two runs. Although the initial vessel position is within the cross-track thresholds, the initial heading error causes the pilot to predict a potential cross track problem and enter the Region #2 control law. This calls for a 5° left rudder to correct heading. The maneuver rate is nulled with a right rudder command at about TIME = 100 seconds, and shortly thereafter the pilot turns steering control over to the helmsman. Although the two runs exhibit similar overall behavior, they are not identical, even though the crab angle precisely compensates water current effects on heading. Differences between the two runs are attributable to the slight reduction in ship's head accrued in Run 5D in opposing the small head-on component of water current during the maneuver. This causes the rudder to be slightly less effective which, coupled with the nonlinear rudder command quantization effects, accounts for the slight differences between the two runs.

Run 5E is a nominal turn sequence, starting with a benign initial condition (no offsets) and no current; Figures 3.34-3.36 show the corresponding time histories. The pilot model turn logic (Appendix F) precalculates a nominal rudder command (20° left rudder) and the along-track position (14,183 ft) at which this command should be applied to negotiate the 45° bend at 8 knots nominal

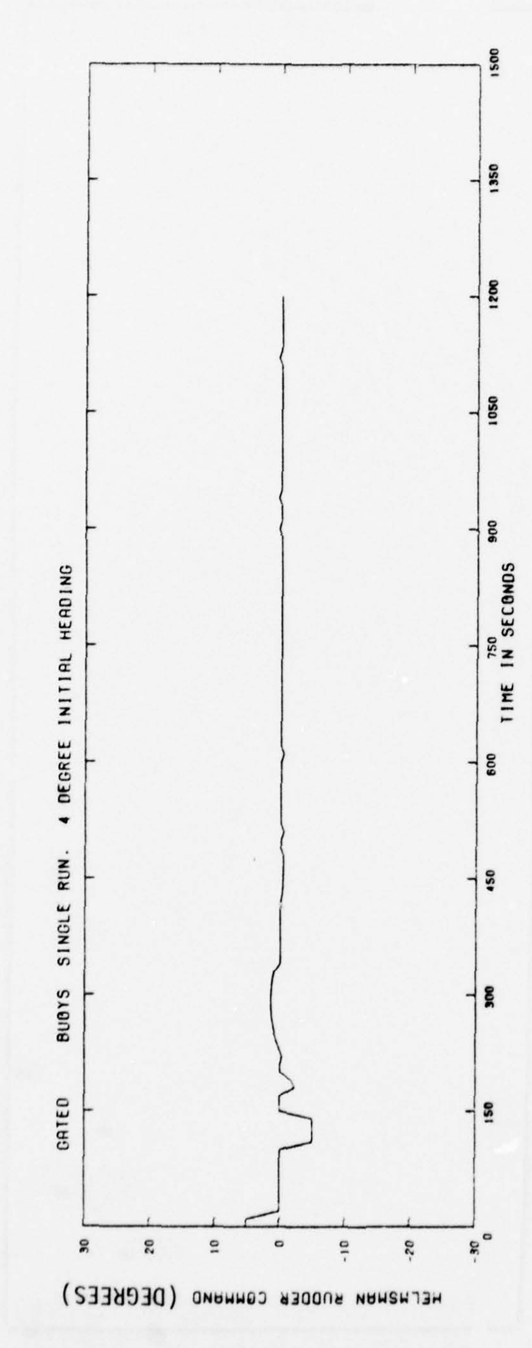


Figure 3.28 Helmsman Rudder Command, Run 5C

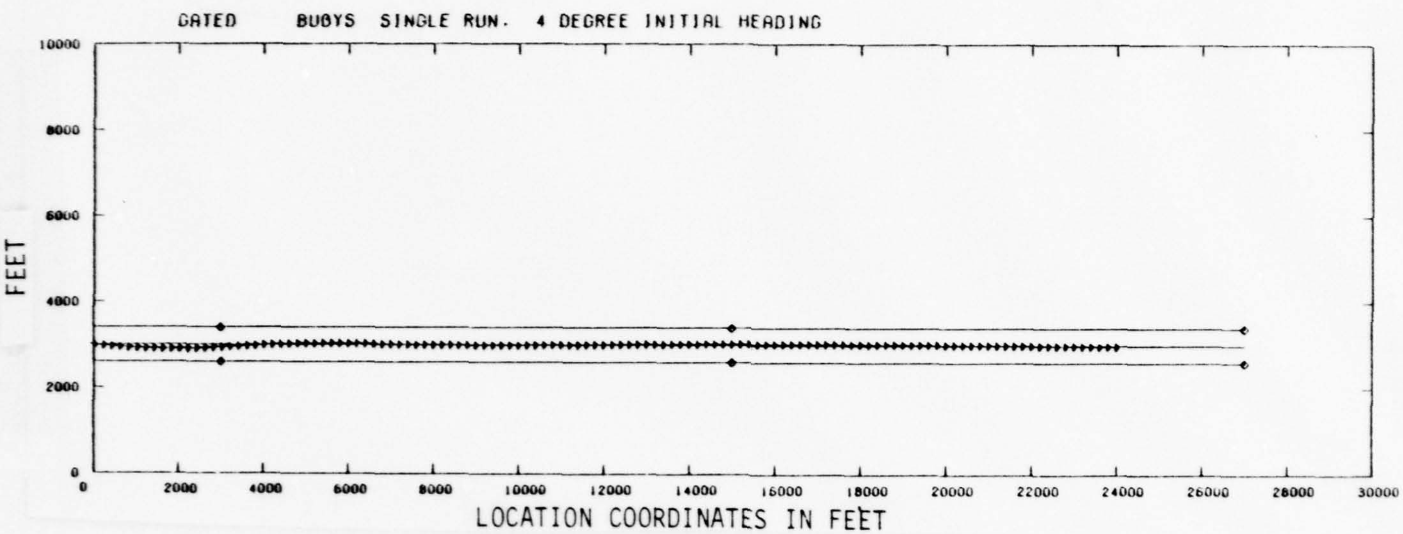


Figure 3.29 Cross-Track Deviation, Run 5C

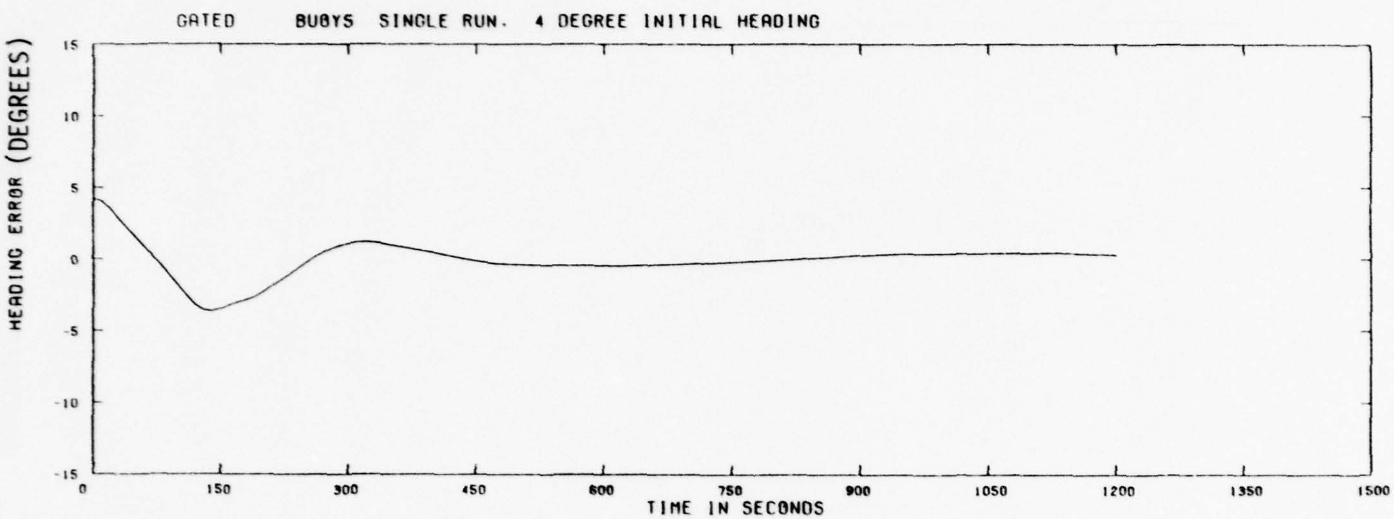


Figure 3.30 Heading Error, Run 5C

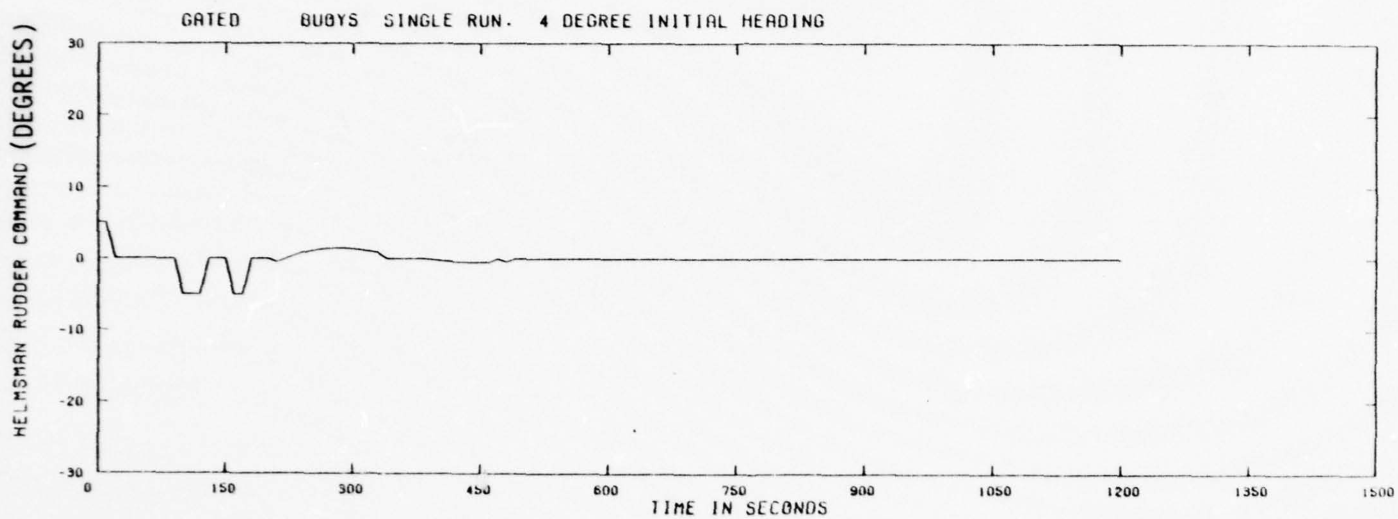


Figure 3.31 Helmsman Rudder Command, Run 5D

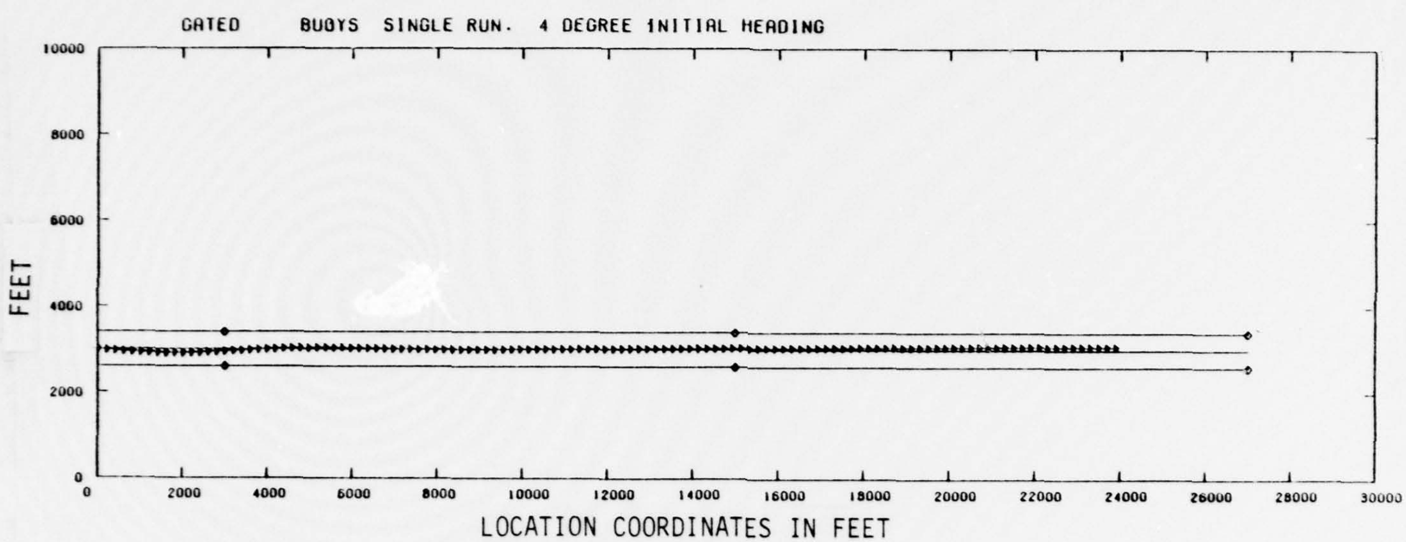


Figure 3.32 Cross-Track Deviation, Run 5D

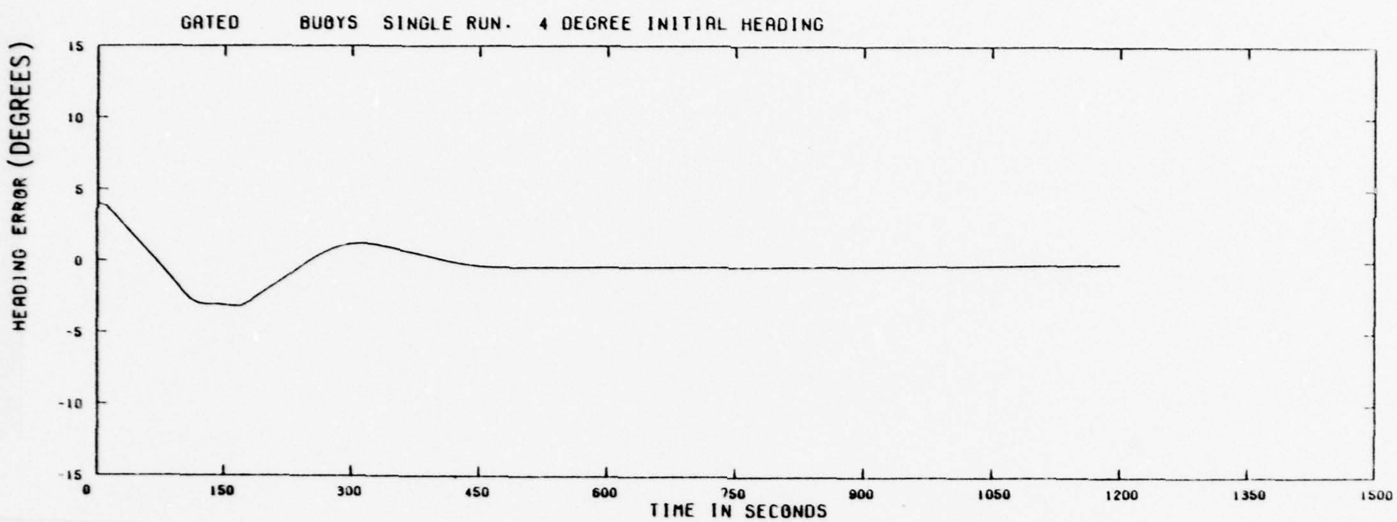


Figure 3.33 Heading Error, Run 5D

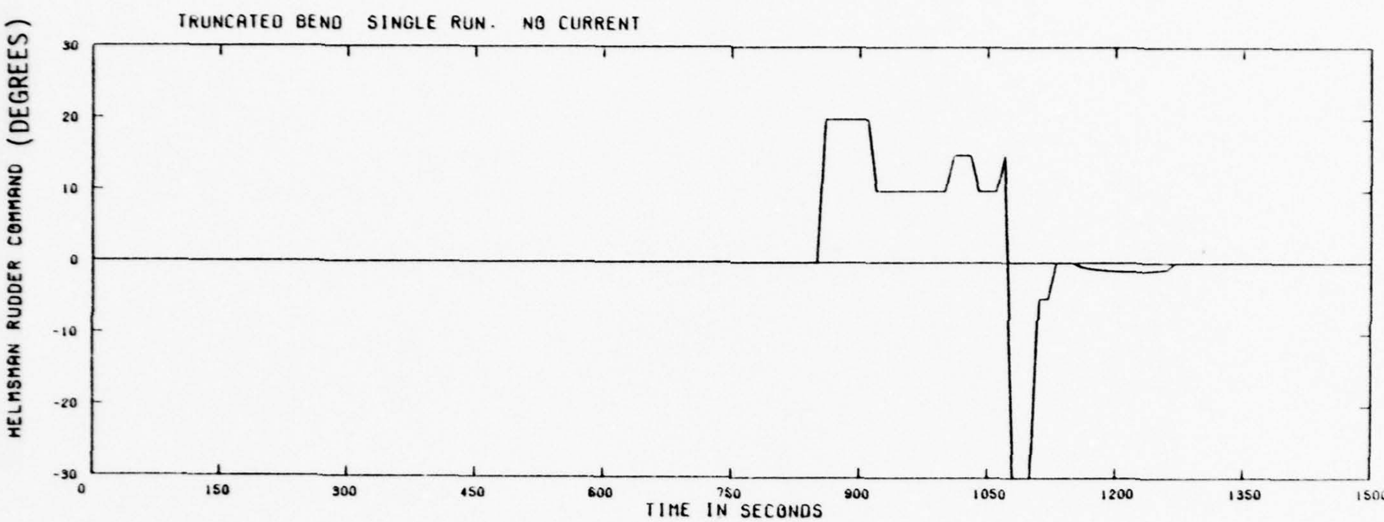


Figure 3.34 Helmsman Rudder Command, Run 5E

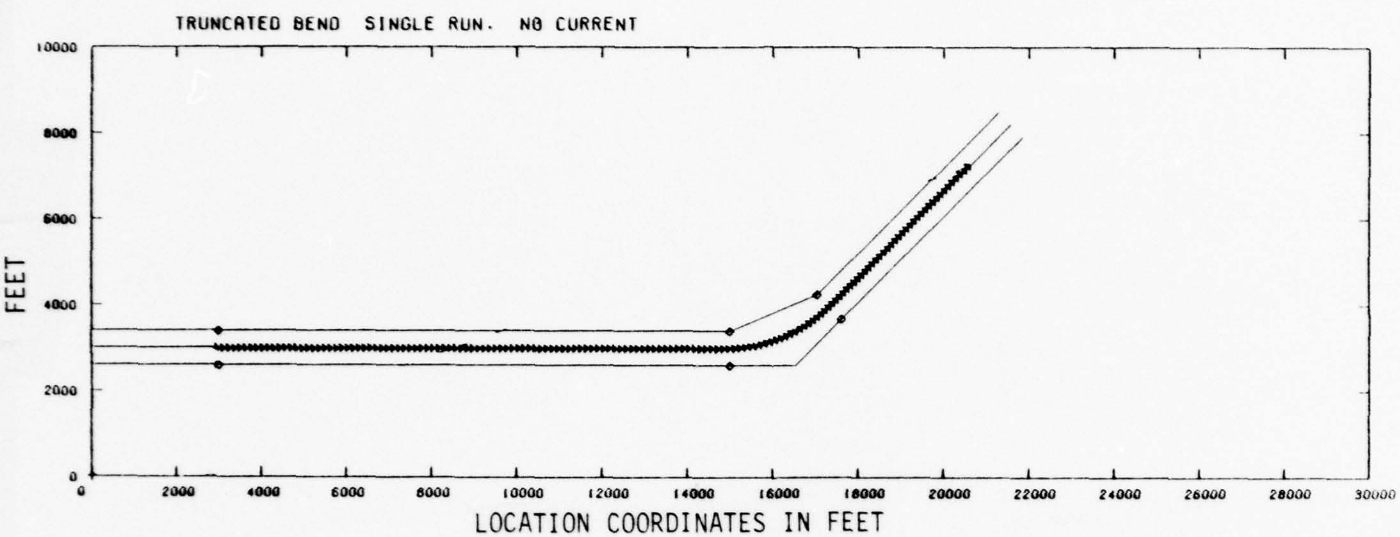


Figure 3.35 Cross-Track Deviation, Run 5E

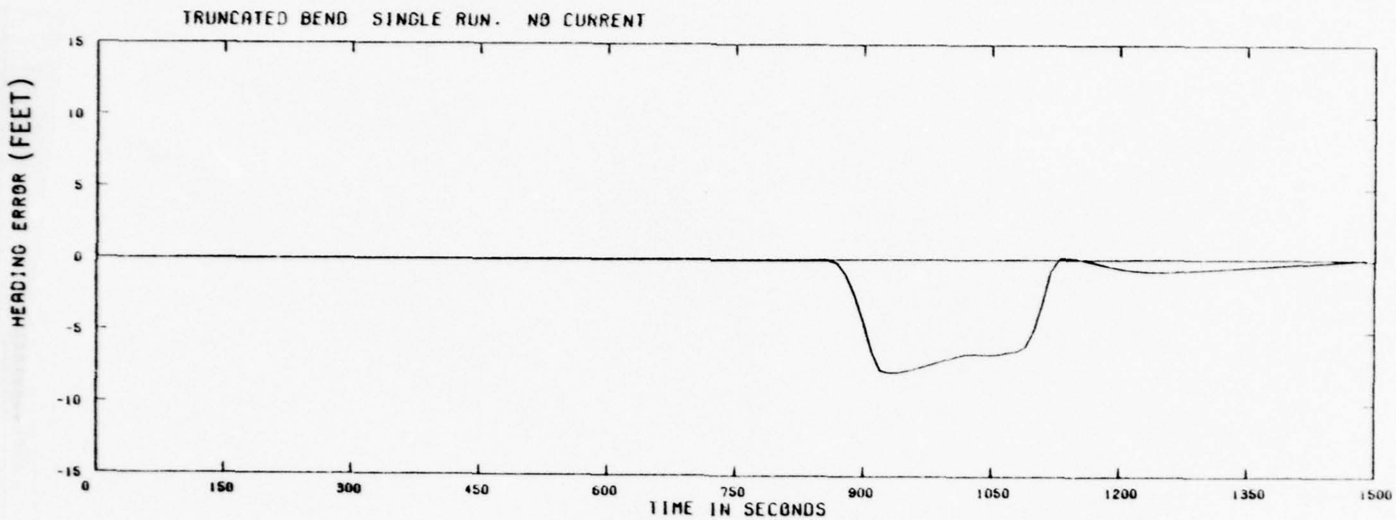


Figure 3.36 Heading Error, Run 5E

vessel speed. Due to the 10-second sampling interval used for this run, passing the nominal turn initiation point is not discovered until an along-track position of 14264 (TIME = 860). At this point, the 20° left rudder command is issued. Sixty seconds later, the command is reduced to 10°; this is attributable to the heading control law which attempts to hold the desired heading during the turn. At TIME = 1080, the pilot nulls his turning rate by issuing a 30° (maximum) right rudder, and backing off to 5°. Thirty seconds after the maneuver, the pilot turns control over to the helmsman to steer the new desired heading.

3.4.3.2 Composite Results Analysis

The component analyses provide insight into the performance capabilities of the individual mariner model elements. A considerable amount of model calibration and validation can be accomplished within the framework of single-run analyses. Further, much can be learned from single-run results, in terms of worst-case conditions and the sensitivity of information utilized to estimation errors. However, the single run results do not consider the interaction of the mariner model elements, nor can they accurately predict the effect of information available on vessel/pilot performance. This is the purpose of composite/Monte Carlo analysis; and it was for this reason that the dynamic simulation-Monte Carlo approach was adopted.

The purpose of performing a Monte-Carlo analysis as a part of the current effort was to demonstrate that the current model can produce reasonable, real world results and to provide insight into how these results can be used to identify validation experiments and, ultimately, to derive establishment/disestablishment criteria.

The case descriptions for the composite/Monte Carlo analysis are presented in Table 3.8. The Monte Carlo runs were limited to ten transits each. In general, this is not an adequate sample

Table 3.8

Monte Carlo Test Cases

RUN NUMBER	DESCRIPTION	COMMENTS/RUN COMPARISONS
1A	Straight Channel,[1] 2-Mile Gated Configuration	Nominal Straight Channel Case
1B	Straight Channel,[1] 1-Mile Gated Configuration	One Mile Gates, for Comparison with Case 1A
1C	Straight Channel,[1] Staggered Configuration, 1-Mile Spacing	One Mile Staggered Configuration, for Comparison with Case 1A
1D	Straight Channel,[1] Single Side Configuration, 1-Mile Spacing	One Mile Single Side Configuration, for Comparison with Cases 1A and 1C
2A	Truncated Bend,[2] 2-Mile Gated Entry and Exit	Nominal Truncated Bend Case
2B	Truncated Bend,[2] 1-Mile Gated Entry and Exit	One Mile Spacing on Entry and Exit, for Comparison with Case 2A
2C	Regular Bend,[2] 2-Mile Gated Entry and Exit	Regular Bend, for Comparison with Case 2A
2D	Regular Bend,[2] 1-Mile Gated Entry and Exit	Regular Bend, One Mile Spacing, for Comparison with Cases 2B and 2C

[1]All straight channel cases utilized vessel speed of 12 knots, 1 knot cross current (heading 180°).

[2]All channel bend cases utilized 8 knot vessel speed, 2/3 knot current (heading 180°).

size by which to derive substantiated conclusions, but was considered adequate for preliminary analysis and to demonstrate functioning of the model. The variations in the performance measures from run to run do not seem to be adversely impacted by the ten trial limitation; i.e., the results, for the most part, can be explained, and one would not expect the sensitivities to be reversed if more trials were made.

The results of these cases will be presented as follows. Test Case 1A will be discussed in some detail, with the intent of describing various model summary ouptut which is available. Only the CALCOMP plot output will be presented (the other output made available by the model is described in Section 3.3.4.2; examples are presented in Appendix F). Subsequent to the discussion of Case 1A, the results of the other cases will be presented and described as needed in order to discuss the run comparisons identified in Table 3.8.

Test Case 1A

Test Case 1A utilized a straight channel, 2-mile gated buoys, 12 knot vessel speed and a cross current (heading 180°) of 1 knot. The actual vessel tracks, as well as the channel/buoy configuration are shown in Figure 3.37. It is appropriate to note that two additional gated pairs of buoys were included beyond those shown in the figure. This was done so that the same information would be available to the vessel at the end of the channel as was at the beginning (this was done in all of the cases run). The extra gates were not shown, since to do so would have further reduced the plot scale.

The same general type of track information is depicted in Figure 3.38, where the average track and the 2-σ ($\approx$ 95%) cross-track deviation bounds are shown. Interpretation of the cross track behavior is as follows. Excellent cross track information is obtained as the gates are approached. This has a tendency to

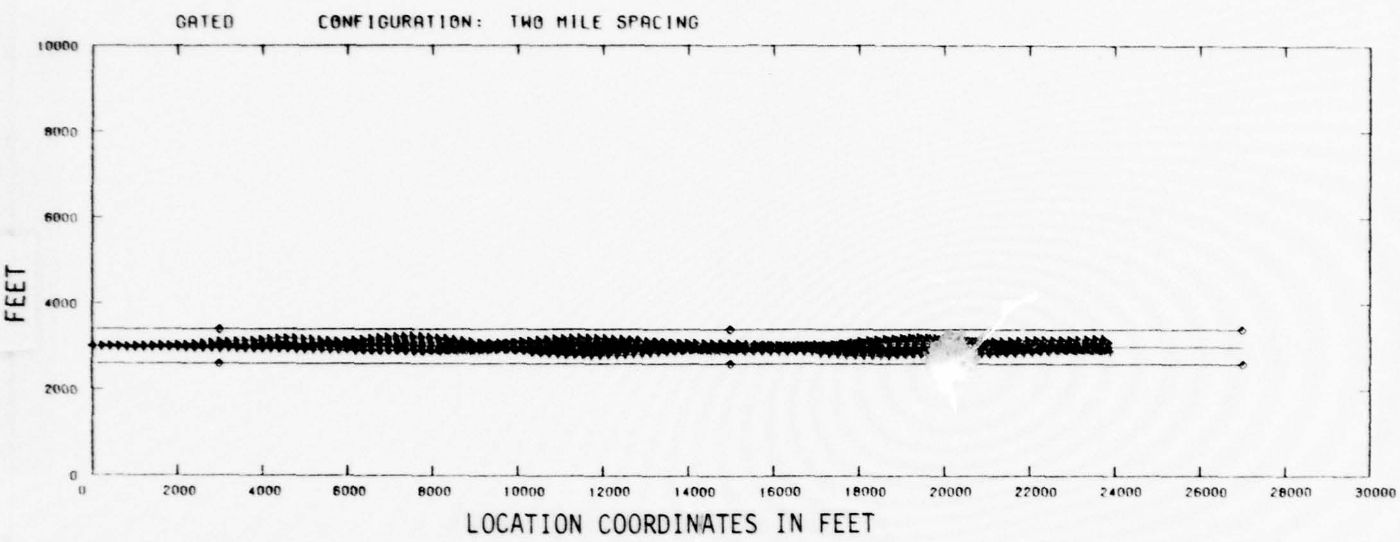


Figure 3.37 Test Case 1A - Vessel Track Results

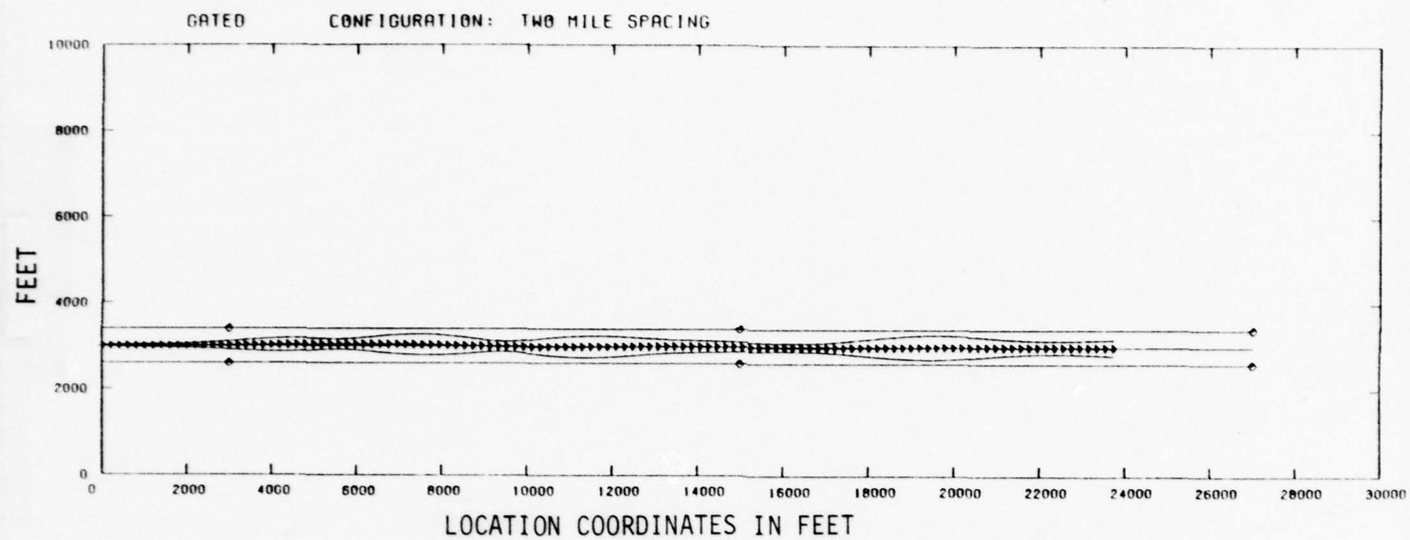


Figure 3.38 Test Case 1A - 2σ Cross-Track Performance Results

reduce cross-track position variance both in between the gates and for some time thereafter. Cross-track variance increases indicative of: (1) less accurate information, and (2) a tendency to overcorrect as the gates were passed.

Figures 3.39 through 3.41 provide plots of the average, the average plus one standard deviation, and the average minus one standard deviation, of the following quantities, respectively:

(1) Pilot rudder command (Figure 3.39).

(2) Cross-track estimation errors (Figure 3.40).

(3) Along-track estimation errors (Figure 3.41).

Test Case 1A vs. 1B

The difference in performance between Cases 1A and 1B provides preliminary insight into the merits of 1 mile gates as compared to 2-mile gates. Cross-track performance for Case 1B is shown in Figure 3.42. Cross-track performance is markedly improved, particularly in terms of the maximum deviations (barring the initial transient effects). The high variance occurring in between the 2-mile gates of Case 1A is nulled out by the additional information made available by the 1-mile gates.

Test Case 1A vs. 1C

Case 1C utilizes staggered buoys. Cross-track performance results are shown in Figure 3.43. These results indicate smoother performance than either of the gated configurations. Cross-track derivations are not diminished by as much as buoys are passed; however, they do not get as large as in the 2-mile gate situation. In contrast to the 2-mile gated case, the smoother performance is also evidenced by the pilot rudder commands; for Case 1C, these are shown in Figure 3.44. The variance of the rudder commands is smaller; there are also more periods where no pilot commands were being made in any of the ten trials. The pilot was in command only

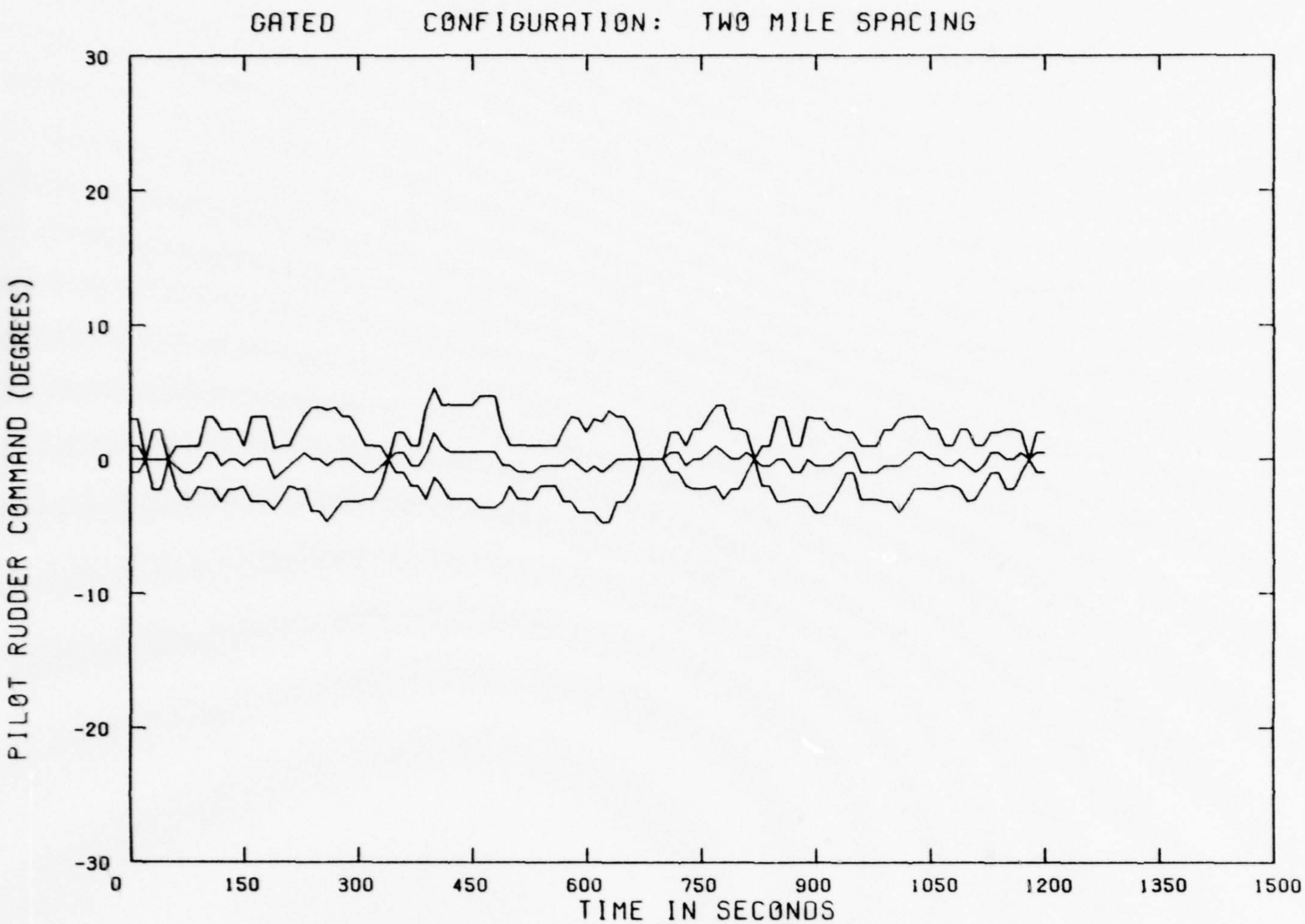


Figure 3.39 Test Case 1A - Pilot Rudder Commands (Mean, Mean $\pm\sigma$)

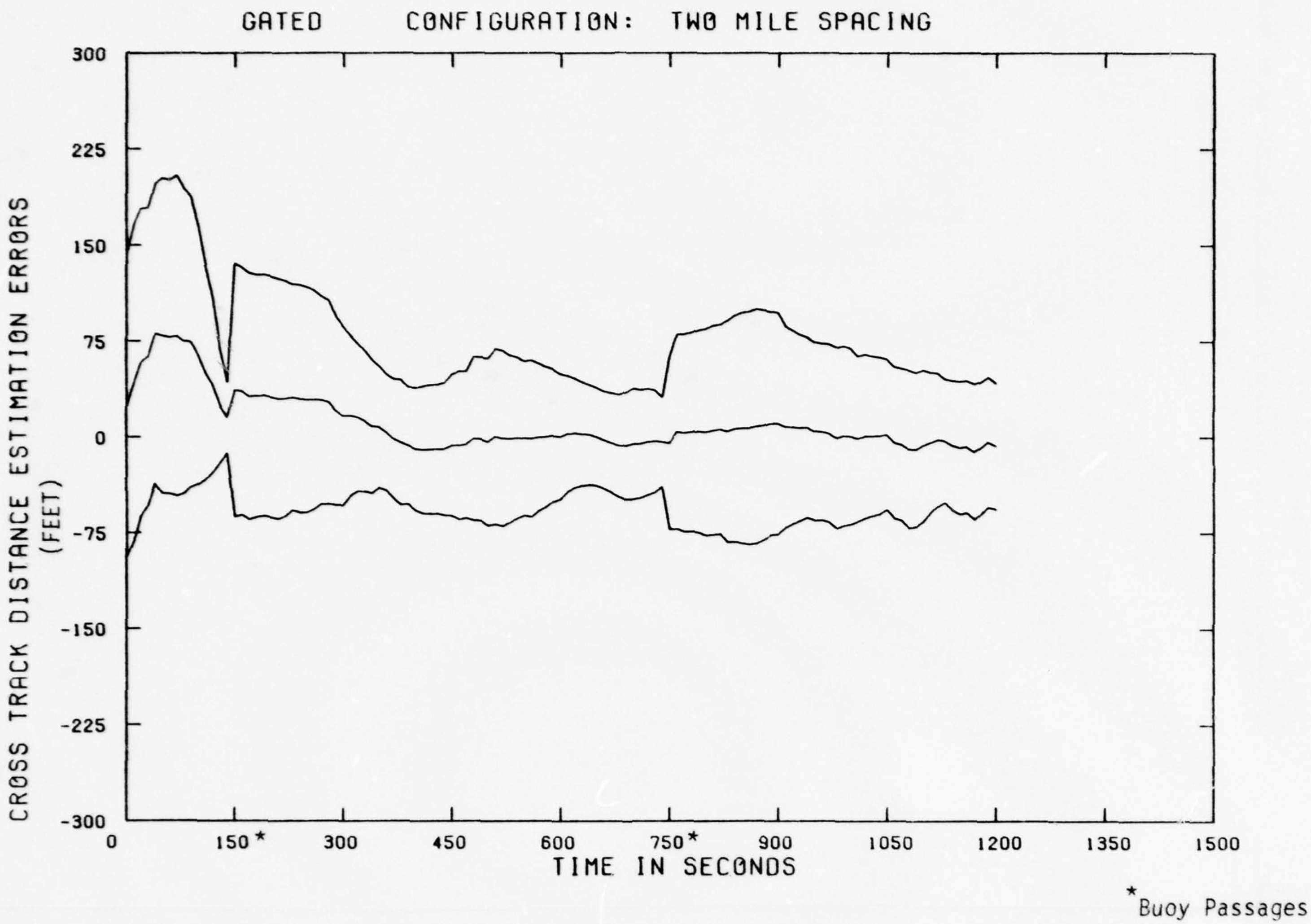


Figure 3.40 Test Case 1A - Cross Track Estimation Errors
(Mean, Mean $\pm\sigma$)

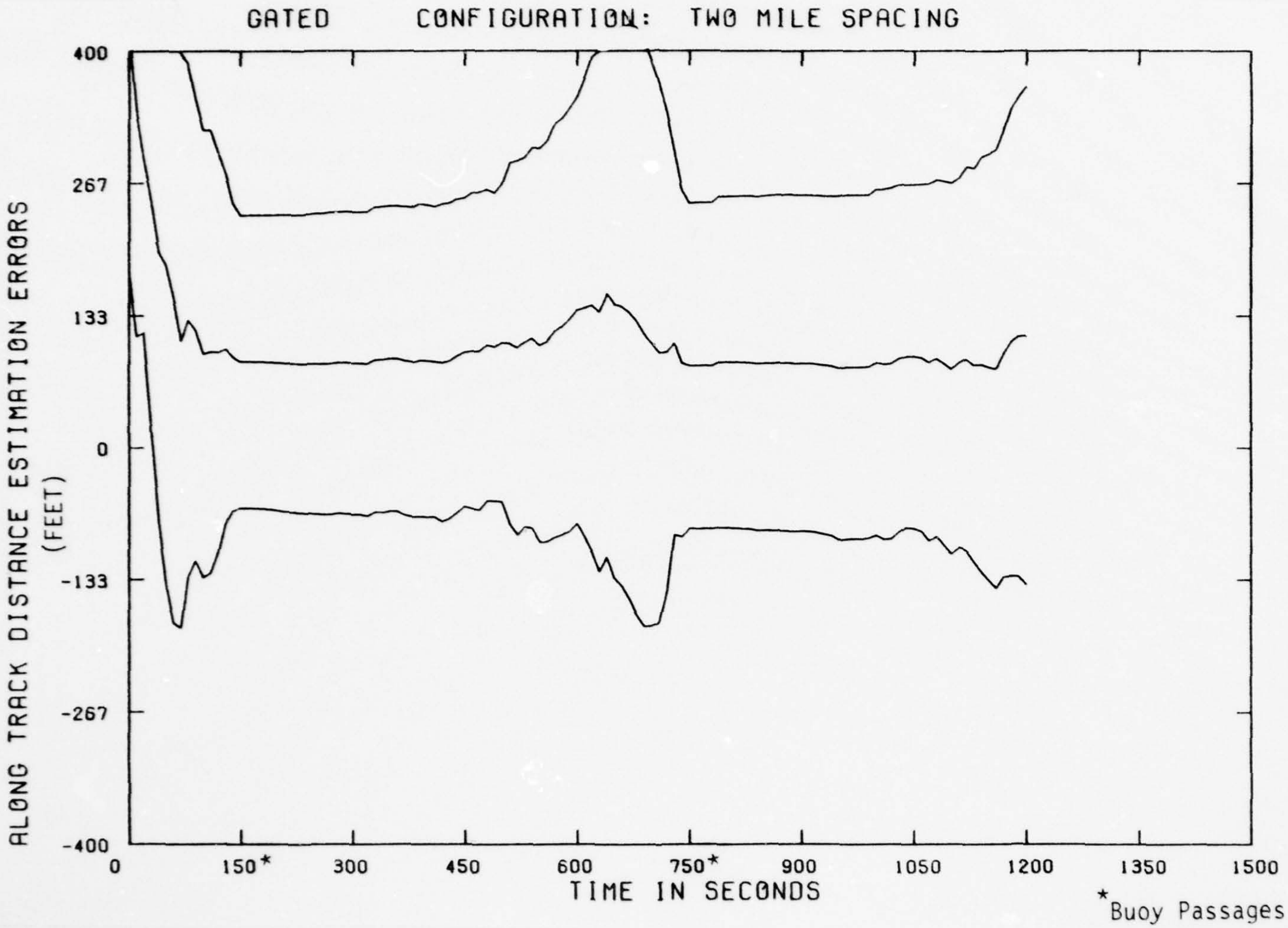


Figure 3.41 Test Case 1A - Along-Track Estimation Errors
(Mean, Mean $\pm\sigma$)

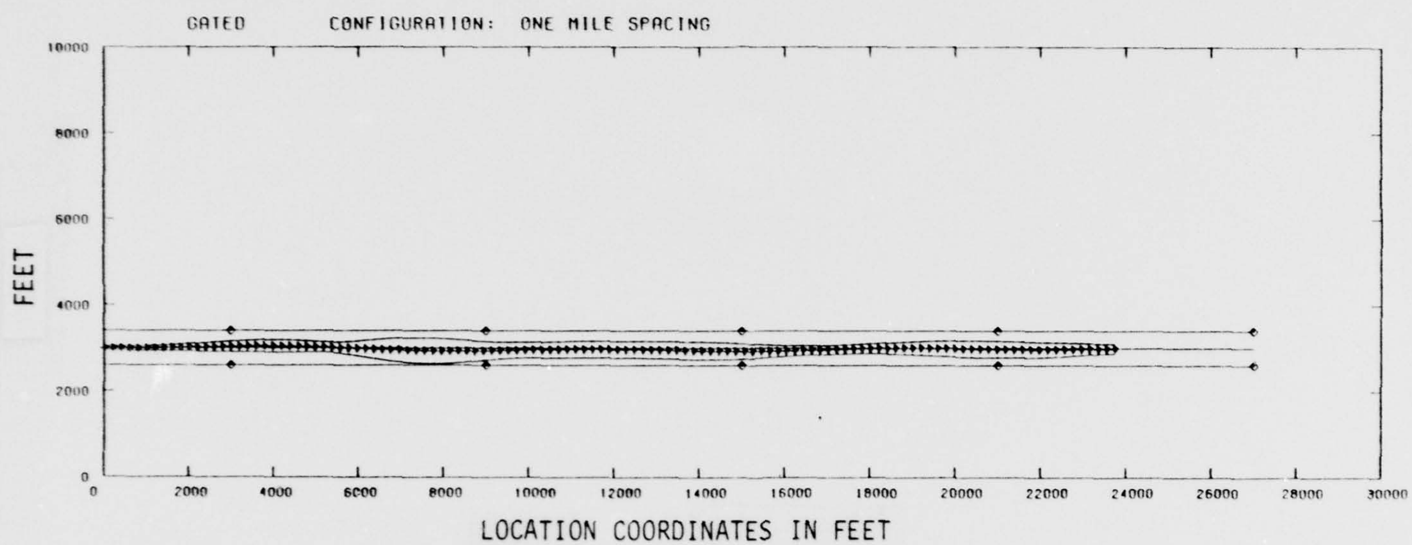


Figure 3.42 Test Case 1B - 2σ Cross-Track Performance Results

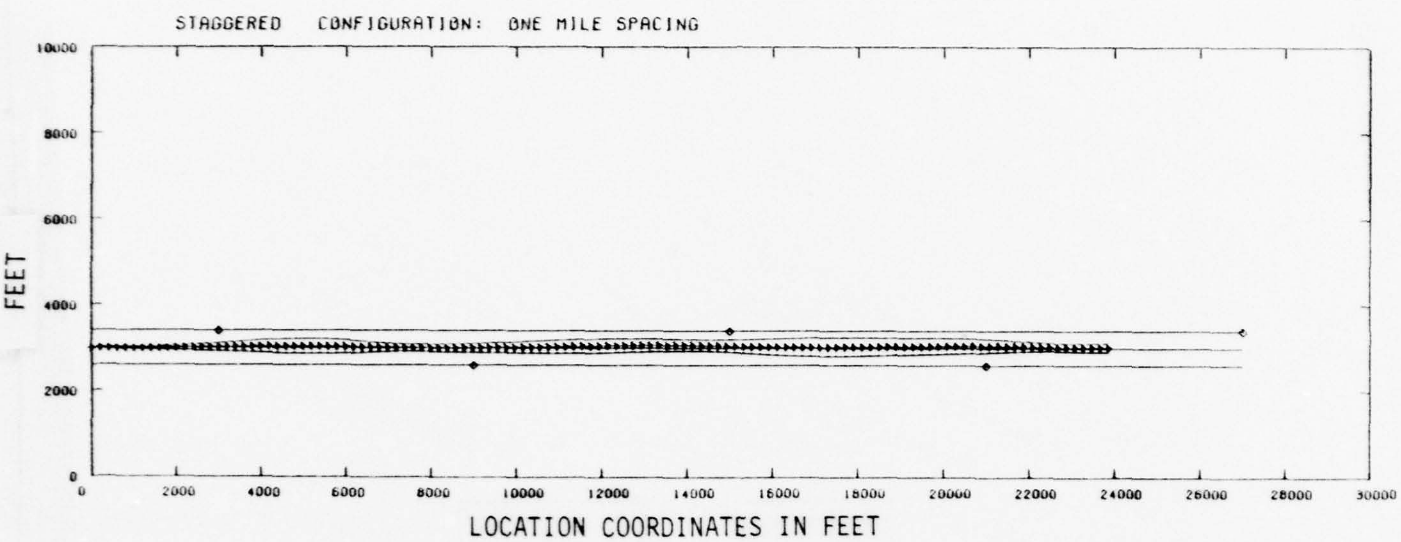


Figure 3.43 Case 1C - 2σ Cross-Track Performance

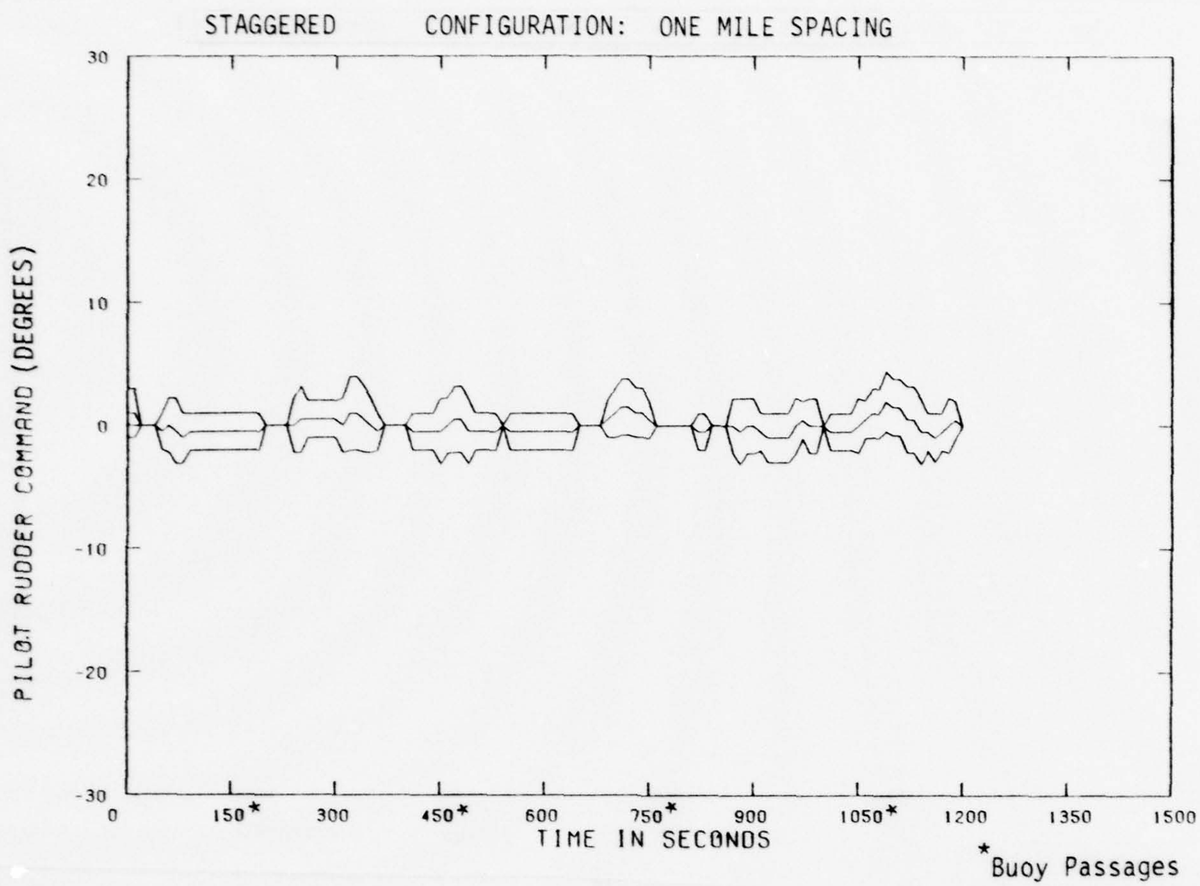


Figure 3.44 Test Case 1C - Pilot Rudder Commands
(Mean, Mean $\pm\sigma$)

13% of the time in Case 1C, as compared to 26% of the time in Case 1A.

Test Cases 1A/1C vs. 1D

Test Case 1D utilized a single side configuration. Cross-track performance is shown in Figure 3.45. Again, smooth performance was obtained; but the cross-track results were worse than any of the other cases. The "smoothness," at least in part, stems from the fact that the biases in the errors do not tend to reverse the sign (left-right status) of the cross-track errors as buoys are passed, as they do in the staggered configuration. In this sense, the single side buoys present a continuity of information similar to the gated situations. Cross-track distance estimation errors also show the greatest degree of uniformity; these results are shown in Figure 3.46.

Test Cases 2A vs. 2B

Cases 2A and 2B involved a truncated bend, 8 knot vessel speeds and a 2/3 knot cross current (heading of 180°). Cross-track performance for each case is shown in Figures 3.47 and 3.48. As before, buoys were utilized which extended beyond the region shown in the plots. These results seem to be affected (more so than the others) by statistical variation induced by the small sample size. Vessels in the 2-mile situation approached the turn in better position than in the 1-mile case. This is not expected. It may be due, in part, to overcorrections made as a result of passing the gate one mile before the turn. Given the preliminary status of the mariner model, no conclusion should be drawn from this result. Similarly unusual results occur at the exit of the turn.

Pilot rudder commands for Case 2A are shown in Figure 3.49 (the results for Case 2B were very similar). The initiation of the

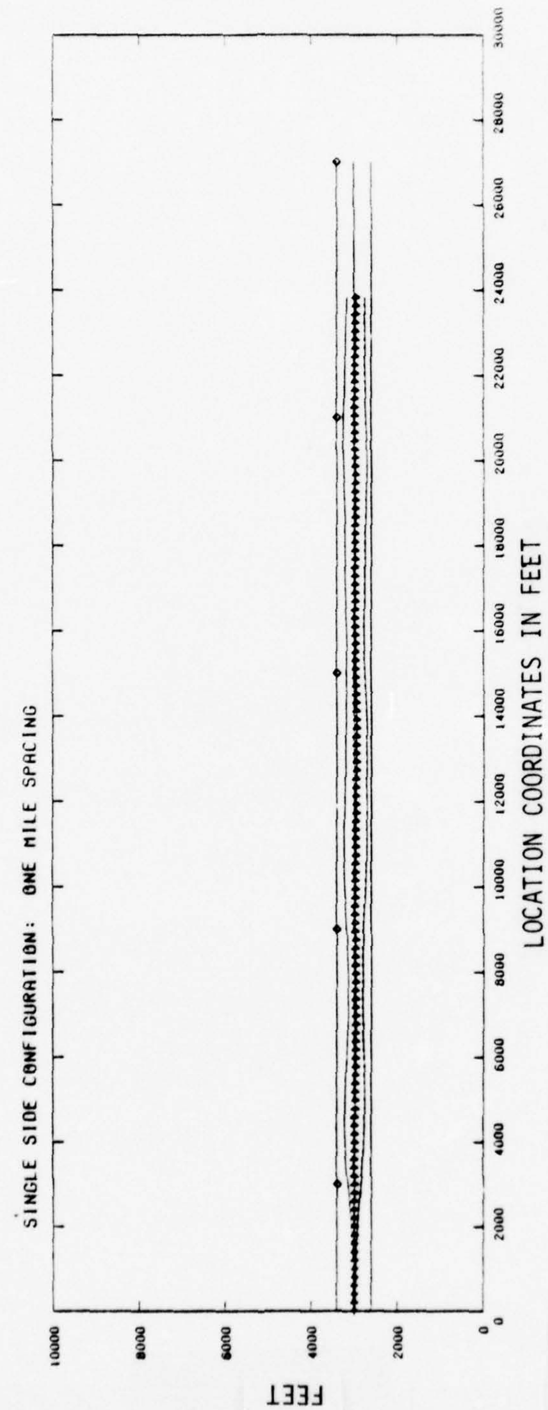


Figure 3.45 Test Case 1D - 2σ Cross-Track Performance

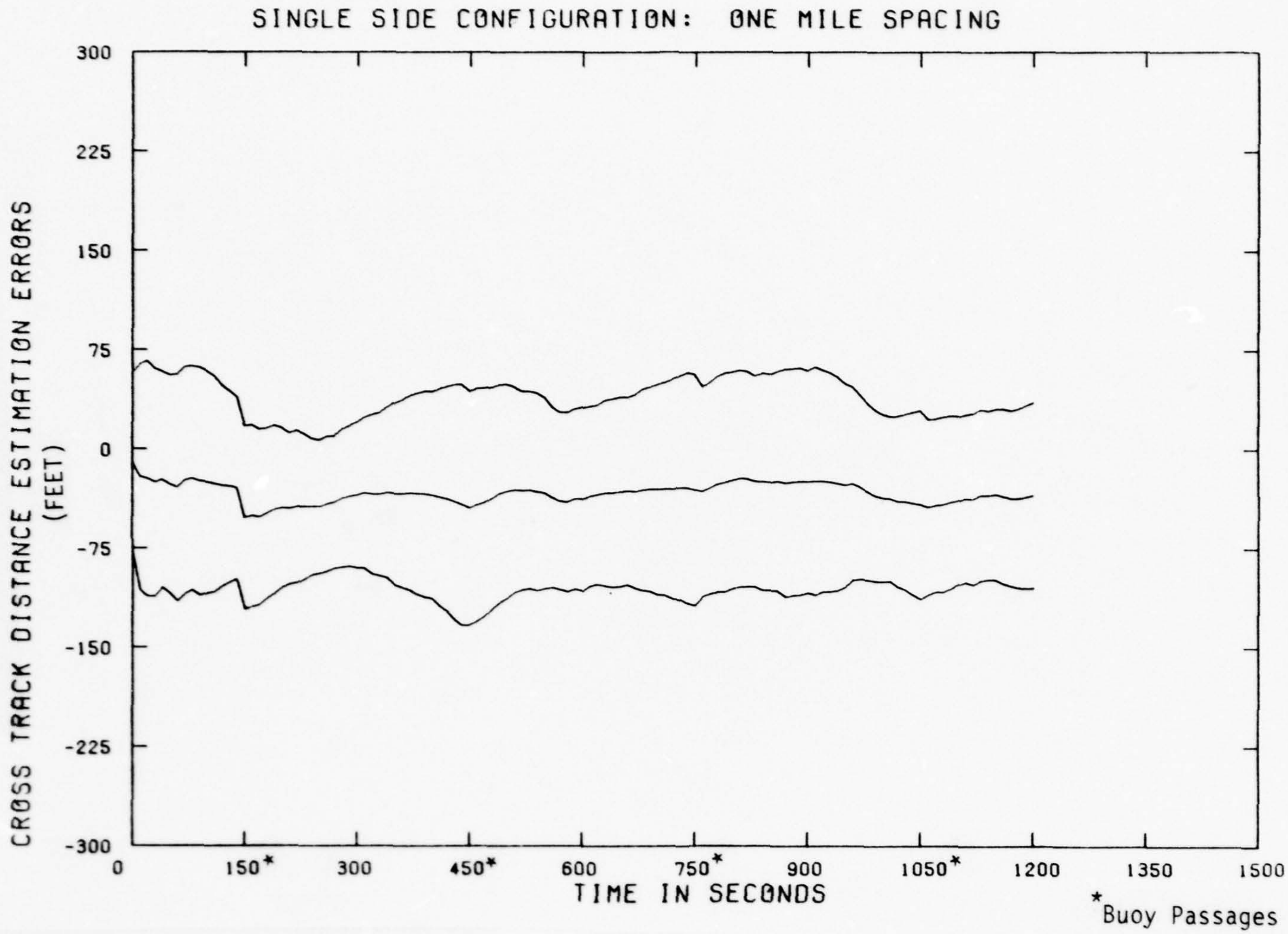


Figure 3.46 Test Case 1D - Cross-Track Distance Estimation Errors (Mean, Mean $\pm\sigma$)

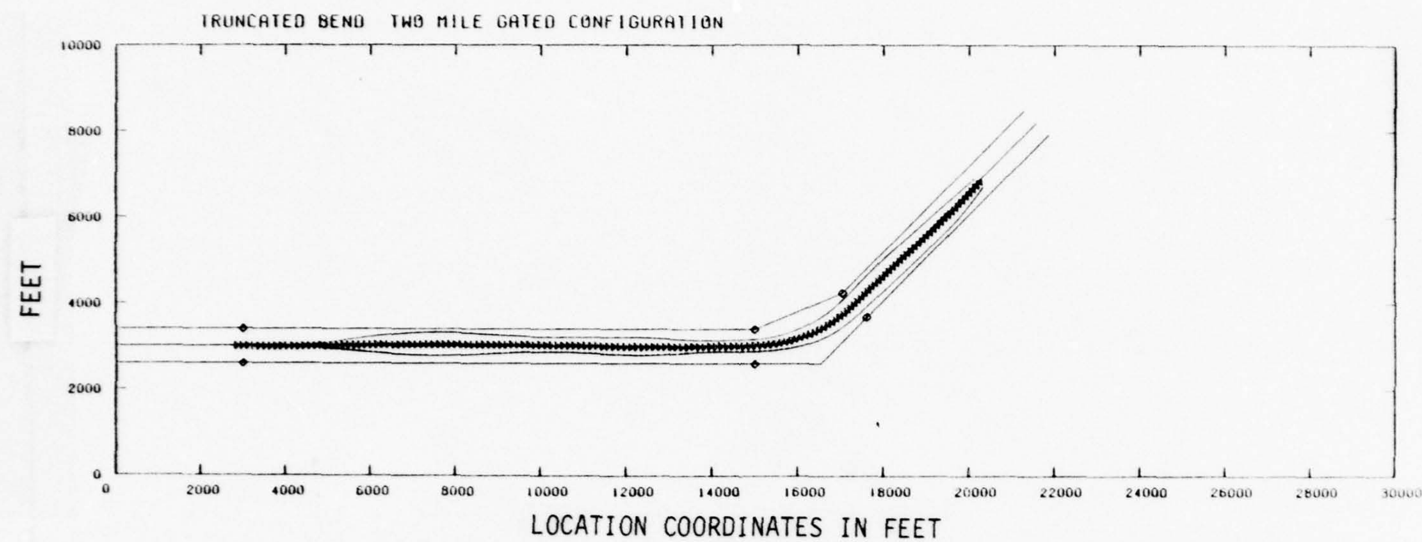


Figure 3.47 Test Case 2A - 2σ Cross-Track Performance

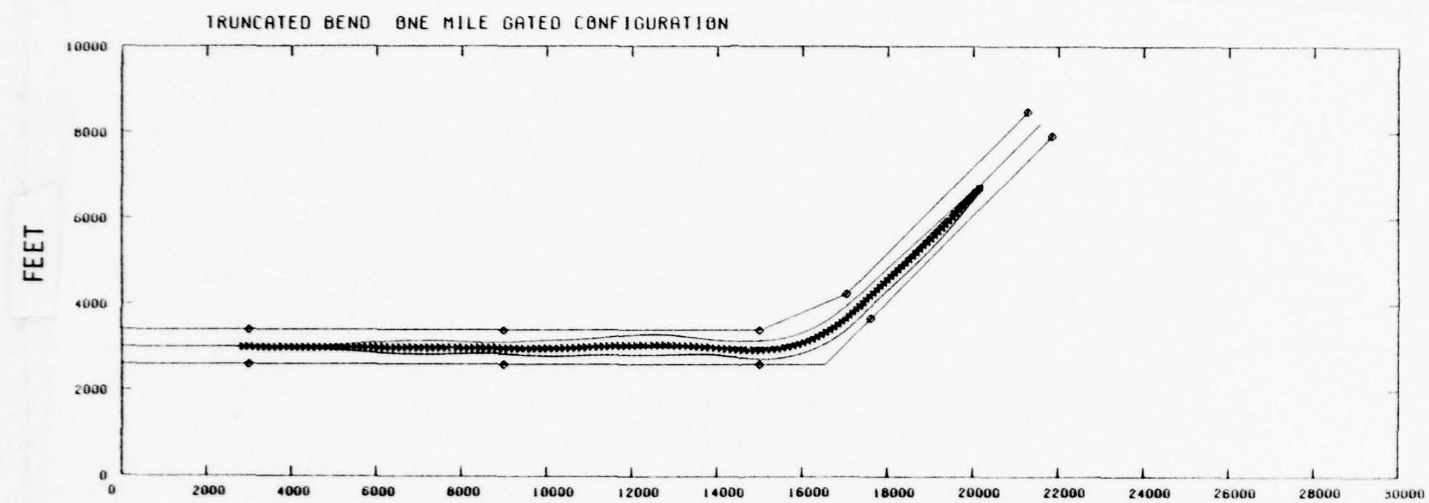


Figure 3.48 Test Case 2B-2σ Cross Track Performance
(Location Coordination in Feet)

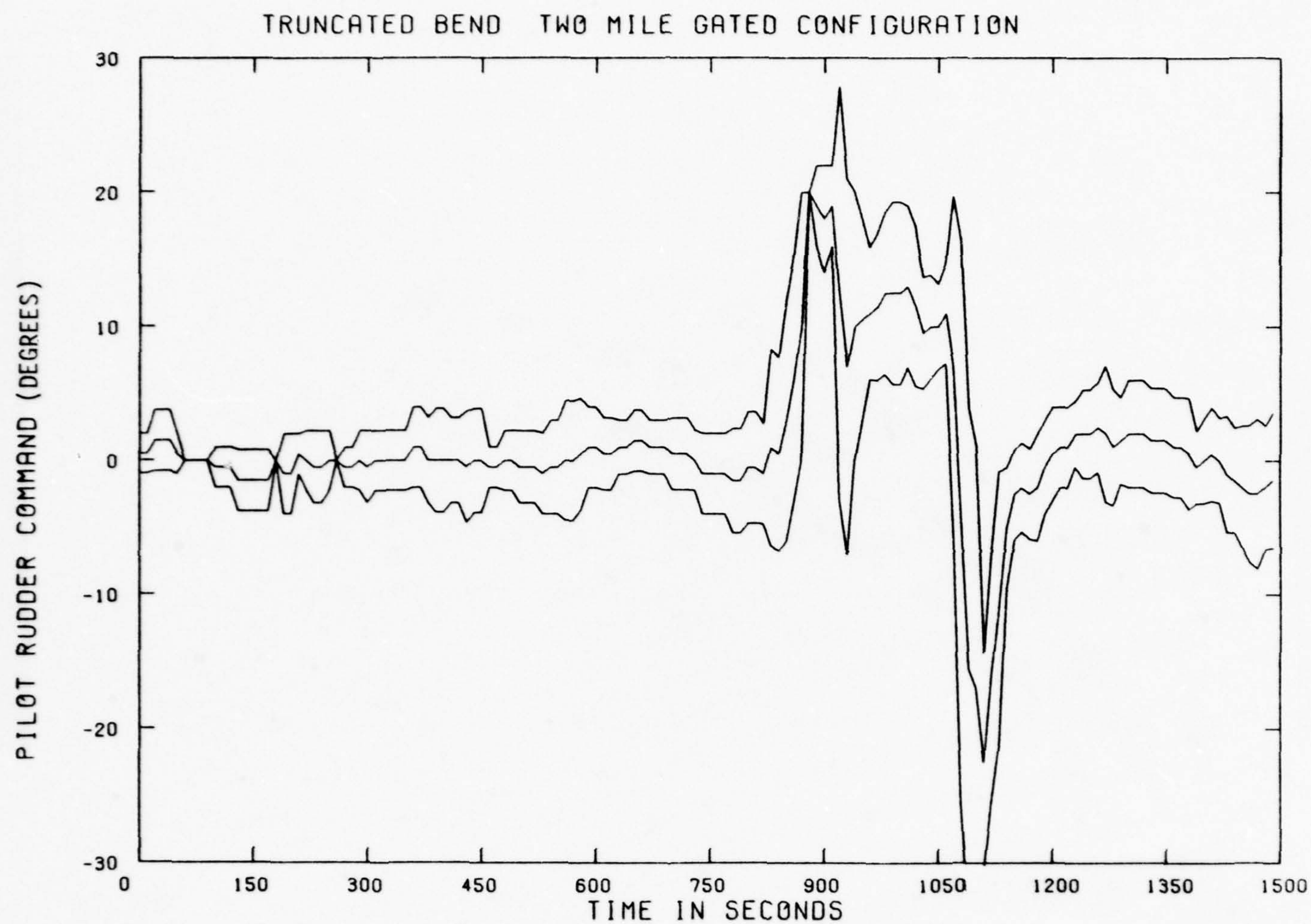


Figure 3.49 Test Case 2A - Pilot Rudder Commands
(Mean, Mean $\pm\sigma$)

turn, rudder variance within the turn and rudder deflection to null the heading rate at the exit of the turn can easily be seen.

Test Cases 2C vs. 2D

Test Cases 2C and 2D utilized a regular (non-truncated) bend, with the same 8 knot vessel speed and 2/3 knot current. Cross-track performance results are shown in Figures 3.50 and 3.51. The relationship between these results and the truncated bend cases is immediately obvious; 30% of vessels grounded in the 2-mile gated case, 40% grounded in the 1-mile case. These results are not necessarily considered unrealistic, given that a current existed and speed reduction was not permitted. All grounding occurred via hitting the inside of the bend. Relative to the truncated bend, the desired track was altered by extending the straight segments into the turn and reducing the radius slightly to permit a nominal 200 ft clearance between the desired track and the corner buoy. The track was kept at the centerline, however.

The regular bend results point out the need for the incorporation of additional mariner decision capabilities. In particular, the current model performs only track-keeping guidance tasks; obstacle avoidance is not considered. This deficiency was known prior to model execution, but incorporation of this capability was not planned until Phase II (as described in Section 3.6.1).

3.5 ESTABLISHMENT/DISESTABLISHMENT CRITERIA

3.5.1 Overview

Design criteria for aid to navigation configurations tailored for specific harbor elements and combinations of elements will ultimately be developed with the assistance of the Navigation System Evaluation Model. This activity is planned as part of Phase II. The purpose of this section is to describe the role

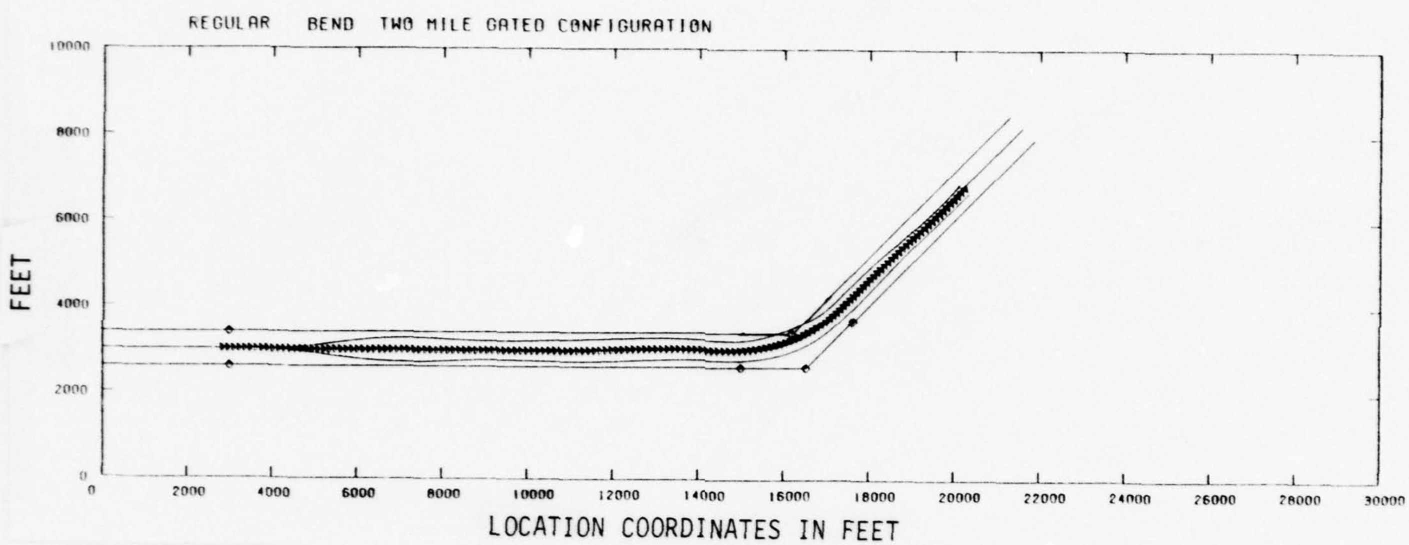


Figure 3.50 Test Case 2C - 2σ Cross-Track Performance

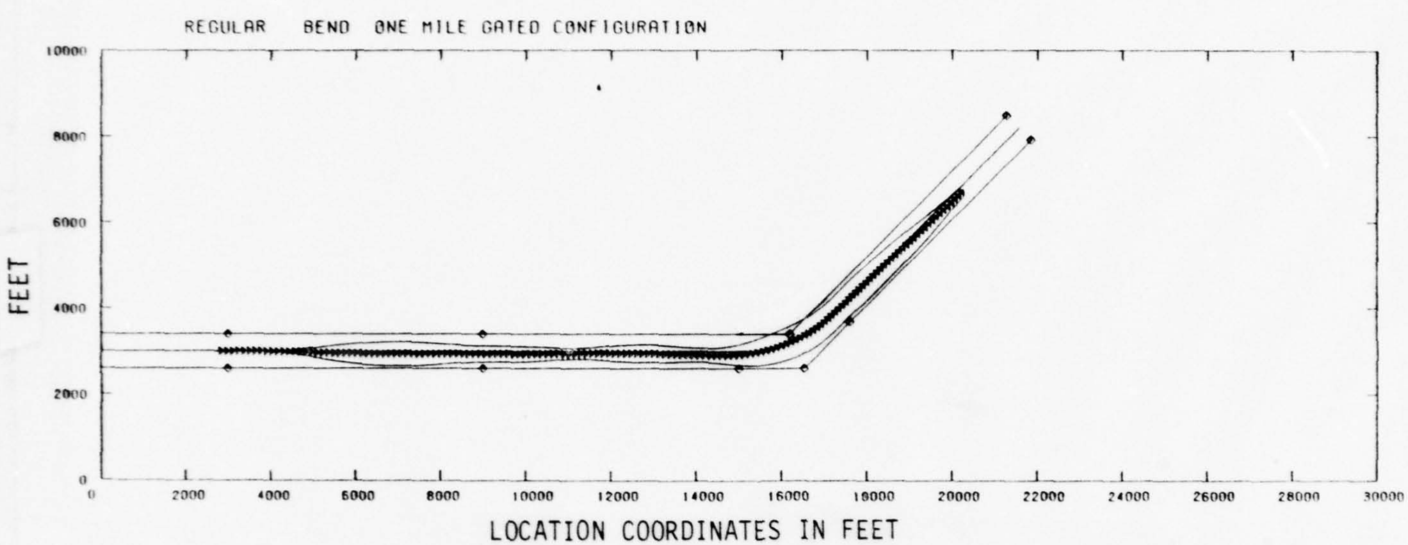


Figure 3.51 Test Case 2D - 2σ Cross-Track Performance

of the modeling effort in the development of establishment/disestablishment criteria, and the interaction of the model results with mariner requirements, and Coast Guard safety, systems management, and budgeting constraints.

3.5.2 Proposed Applications

The basic objective of aid to navigation evaluation criteria is to provide guidelines for operating personnel responsible for the establishment, disestablishment, and maintenance of aids to navigation systems. It is certain that criteria cannot be developed that will apply to all possible situations nor is there a necessity for them to do so. However, results of discussions and interviews reveal the general feeling among mariners that the Process of Navigation is basically incremental through a large number of harbor elements which can be considered "common" to all navigable waterways. These common elements seem amenable to management by a generally applied set of criteria, which define for each element an adequate set of aids and, at the same time, ensure the most efficient utilization of available resources in implementation and maintenance.

3.5.3 Criteria Development

At the Coast Guard Headquarters level, the development of criteria will be largely a matter of comparative analyses of alternatives; such analyses requiring two major sets of information.

- The characteristics of harbor elements and combinations including accuracy requirements.
- Quantitative measures of the effectiveness of aid configurations available for application to the harbor elements.

Each of these major sets of information represents a multidimensional matrix when all parameters impacting upon them are

taken into consideration. It is possible, however, based on the results of the Phase I effort, to estimate areas requiring parameter validation, identify the method used by the PON model in criteria development, and postulate at least the basic form and content of the criteria so developed. Qualitative criteria, directed to certain types of operation, were observed during the expert interviews and discussions held early in Phase I. For example:

- "Unlighted buoys alternated with lighted buoys in a marked channel constitute anything from a nuisance to a menace".

- "The seaward side of harbor entrance channels require the installation of an approach buoy at least one mile from the channel entrance to permit vessel/channel alignment prior to entrance therein".

- "Long range lights within a harbor complex are rarely used and may have a blinding effect on navigators passing close aboard".

The foregoing are statements of opinion by "experts", nothing more (or less). They are, however, illustrative of the type of qualitative input available in the aid configuration design process. The major problem in the development of analytic criteria will remain the assignment of numbers to the various aspects of configuration design and operational use of visual aid systems. Some quantitative guidance is provided in CG-222, as discussed elsewhere in this report. An example of which follows:

- "Buoy spacing will be insofar as possible:

  1 mile in exposed areas
  3/4 mile in semi-exposed areas
  1/2 mile in sheltered areas."

Questions might naturally arise regarding the choice of numbers. Their basis is undoubtedly an "experienced judgment." Equivalent alternatives exist. For example, why not install buoys of twice the nominal visual range at one mile spacing in

sheltered waters? The buoys would be larger, but with only half the number, could conceivably reduce service and maintenance time on the part of responsible vessels and personnel.

The foregoing are examples of both qualitative and quantitative inputs to the criteria development process. Verification of such criteria and examination of alternatives require the application of specific knowledge regarding the process of navigation. Why is the entrance buoy previously mentioned considered a necessity? The answer lies in the techniques used in maneuvering a vessel into the channel entrance so marked. Why, in the navigation of large ships through channels, are blind buoys considered a nuisance? Apparently, from the point of view of the navigators, the Process of Navigation does not involve their use but does involve the necessity of avoiding them.

It is through the use of such qualitative criteria that the present system configuration has evolved. The application of the Navigation System Evaluation Model and the Process of Navigation Model, when complete and the input data refined, will permit quantitative comparison through testing of a defined navigation technique in alternative aid configurations. The experimental process, given the refined input data, will accurately represent an actual mariner, navigating an actual ship through a defined harbor element, marked with alternative aid configurations. Resultant analysis will yield quantitative data in the same form as that acquired, for example, in large scale ship simulator experiments. The difference lies only in the time and cost savings with which multiple runs of the same experiment can be accomplished. The situation variables may then be reduced to statistically definable quantities for comparison with alternatives similarly developed and defined.

Use of the criteria at operating levels (a district or group) will require identification of the harbor element to be marked, local traffic profiles and impacting environmental conditions.

The criteria for marking will appear, as conceived at the present stage of development, in the form of operational parameters. i.e. range of visibility, applicable basic configurations, etc. The command decision at the local level will then be based on consideration of resources locally available that will best satisfy the quantitative criteria.

3.5.4 Criteria Parameters

The Navigation System Evaluation Model will improve analysis of the interrelationships of the following parameter sets and subsets:

(1) Channel Elements

- Straight channel
- Channel entrance/exit
- Channel width change (no change in direction)
- Bend/turn requirements (with or without a change in width
- Junction

(2) Constants and Modifiers

- Length
- Width
- Control/project depth
- Traffic profile (size, number, maneuverability)
- Turn radius
- Environment effects (current, wind, usual sea state, meteorological visibility)
- Alternative routes available

The foregoing parameter sets are relatively simple to define. Additional elements or modifications will undoubtedly result as Phase II progresses, but data relating to the foregoing seems readily available.

In view of the opinion of most interview subjects that the Process of Navigation through a harbor is incremental, with the great majority of information extracted from aids in the immediate area, the Navigation System Evaluation Model will deal conceptually with basic "building block" visual aid configurations. Any existing or proposed aid system can be synthesized using the following basic configurations:

Basic Aid Configurations:

- Single aid (point reference, no lateral significance)
- Perpendicular gate
- Cocked gate
- Gated pair
- Single line (one side marking)
- Staggered triplet (on side, off side)
- Heading line (navigational range)

Each of the foregoing is composed of single aids with defineable characteristics as follows:

Single Aid Characteristics:

- Height
- Physical cross section
- Radar cross section
- Lighted/unlighted
- Color
- Shape

The effect of the foregoing (when combined with height of eye) is primarily a determination of the nominal visible range of the aid and the results are well documented.

Certain alternatives are available in the implementation of the basic aid configurations listed above. These primarily are of the form of spacing between aids on the same side of the channel (gated and single sided configurations); spacing between buoys on alternate sides of the channel (staggered configurations),

and the navigational range design parameters; H (height of far aid), h (height of near aid) and d (distance between aids). It is expected that definite quantitative relationships among the foregoing parameter sets will be developed for application to implementation criteria. Intuitively, for example, these would seem to be a measurable, optimum aid spacing to channel width ratio (S/W) for gated, staggered, and single aid configurations.

The final set of data required for input to the criteria development equations involve the effectiveness of the aid configuration. These data are the least amenable to quantification at the present time and will yield only to a combination of real-time experimentation to establish valid value limits and fast-time, multiple experimental runs to provide the necessary statistics of results within those limits. The term "effectiveness" normally includes other than operational factors (usually economic). For purposes of operational criteria development, the term accuracy adequately defines the necessary measures.

Accuracy of a visual aid system is inextricably linked to the Process of Navigation. The mariner has a choice of information parameters available to him from a given aid to navigation. Which of these parameters he measures, and the accuracy with which he measures them, determines the accuracy of the system. Appendix C considers in some detail the information content of the various basic configurations. The accuracy of the configuration defies quantification unless the accuracy of the measurement by the mariner of the selected information bits is included. This information, when compared to the accuracy requirements resulting from analysis of the harbor element and modifiers of Section 3.5.4 (1) and (2) will result in data suitable for development of criteria for an "adequate" configuration.

3.5.5 Summary

The preceding paragraphs have described those parameters having the greatest potential impact on the development of criteria for the design or modification of aid to navigation configurations. The emphasis has been on visual aids since analytic techniques for radio aid evaluation are readily available. It is recognized that the problem, even in its simplest application is multi-dimensional and that certain necessary input parameters remain to be quantified. The Phase II effort of the study will accomplish this quantification. The Navigation System Evaluation Model may then be extensively exercised, alternatives examined, and feasible criteria developed.

3.6 ADDITIONAL EFFORT REQUIRED FOR PHASE II

The SCI (Vt) approach to the Phase I study activity can be briefly characterized by the following objectives (and results):

(1) Identification of essential elements of the process of navigation

(2) The development of a functioning Navigation System Evaluation/Process of Navigation model, and

(3) The development of an overall aids to navigation evaluation procedure.

These three study characteristics are complementary and necessary. The intent of this approach in Phase I was to demonstrate that the capability exists to (a) obtain aids to navigation performance results, and (b) to synthesize these results into an orderly, workable evaluation methodology.

The purpose of the development of a functioning Navigation System Evaluation/PON model in Phase I was to demonstrate the viability of the overall modeling approach. Past experience has

indicated that the successful development of a detailed model and its software does not necessarily ensure successful (i.e., validatable) model performance. This is particularly true in state of the art human dynamics modeling. Thus, the design activity was directed so as to generate intermediate results at various design stages, and these results were examined for reasonableness and consistency with available data.

The Phase I model was designed as a preliminary model. Only one vessel and one "mariner type" were considered, and the navigation information processed by the mariner model was limited to buoys (and USCG ranges) and selected on-board displays. The pilot guidance/control functions included turning and return-to-course capabilities. The activities undertaken, however, encompassed the most difficult modeling problems. If the Phase I model had been designed only to utilize Loran-C course deviation read-outs, the modeling activity would have been straightforward. SCI (Vt) has developed many dynamic simulations of this type. Very little would have been learned and the feasibility of the approach would remain suspect. Such is not the case, however, because while considerable model development lies ahead, questions of developmental feasibility (risk) are essentially nonexistent. While it is inadvisable to state that the risks associated with validation are completely negligible, these risks have been sufficiently reduced by the preliminary results thus far obtained so as to fully justify feasibility of the approach and continued effort.

The approach taken by SCI (Vt) for the development of an aids to navigation evaluation procedure is designed to minimize the requirements for the gathering of additional data. The structured model development allows for a clearly designed experimental plan that focuses on a subset of possible experiments and collection of "real" data required for validation purposes only. Otherwise, the data collection approach for a full aids to navigation

evaluation would be too extensive. Without a full appreciation of SCI (Vt)'s method of approach to the evaluation procedure, one might envision extensive experimentation in certain operational conditions that give little, if any, insight into evaluation of navigation aids.

In light of the achievements of the Phase I activities, the remaining effort, to be accomplished in Phase II, can be categorized as follows:

(1) Incorporation of additional model capabilities

(2) Expansion of the study data base utilizing sea trials, CAORF and other simulation facilities

(3) Model validation

(4) Application of the model and evaluation techniques for the derivation of establishment/disestablishment criteria

(5) Conversion of the model for USCG use

(6) Delivery, instruction, and documentation.

Each of these Phase II activities is discussed in the following subsections.

3.6.1 Model Development

This subsection addresses the incorporation of additional capabilities into the NSEM/PON model. Model refinement (i.e. extension and validation of existing capabilities and functions) is described in Section 3.6.3. The model additions are described in terms of the submodels affected, which include:

(1) Navigation System Evaluation Model (as distinct from the PON)

(2) Process of Navigation Model (PON) — State Estimator

(3) PON — Decision and Control Submodels

(4) PON — Dynamics

(5) Overall PON Executive Elements

3.6.1.1 Navigation System Evaluation Model Enhancements

Much of the modeling effort to be devoted to the NSEM will involve input/output and user convenience modifications. These refinements are essentially non-technical and need not be addressed. The two primary areas where additional technical effort is required are the development of the "requirements determination/configuration guideline" portions of the NSEM (the NSEM Part (I) processing) and the refinement and incorporation of additional vessel safety and traffic facilitation measures.

It was initially expected that more of the NSEM Part I processing elements would be developed than was in fact accomplished. As the study progressed, however, it was established that much of the inputs to the Part I processing can be and should be obtained from the Part II (PON) results. Development of these portions of the NSEM Part I model was therefore considered premature, and this activity is planned for Phase II.

The NSEM Part I output is intended to provide guidance of several types to the model user. The output will include:

(1) perceived mariner requirements

(2) previous PON (NSEM II) results (in summary form)

(3) aids to navigation configuration guidelines, and

(4) recommendations regarding parameter selections (vessel speeds, desired tracks, etc.) for input to the NSEM Part II).

Early in Phase II, a detailed design of the model structure to accomplish these functions will be developed. As the PON validation activity progresses, the PON results (as well as other information, interviews, etc.) will be analyzed in order to derive the most

meaningful manner in which these results can be summarized and displayed for interpretation by the model user. As this is accomplished, the results will be incorporated into the NSEM (I) model.

With regard to vessel safety and traffic facilitation (performance) measures, much work, in terms of refinement and validation, has yet to be done. This was as expected, since it was known that significant accomplishments in this area could not be made in Phase I. As has been mentioned in other sections of this report, the model has been structured to permit expedient incorporation of additional performance measures. Section 3.3.4 presented a list of specific performance measures which are to be added to the model at the outset of the Phase II effort. Subsequent to the completion of that effort, considerable performance measure refinement will take place.

3.6.1.2 State Estimator Enhancements

In the context of an "aids to navigation" study, the State Estimator is the key element of the mariner model. While the Phase I modeling activity has been extensive, several specific State Estimator functions, required for Phase II, have not been addressed. The primary additional capabilities which will be developed in Phase II are summarized below:

(1) Incorporation of On-Board Radar as an Aid to Navigation. This will be accomplished by careful examination of the information made available by radar, how and when it it used, and an analysis of both radar equipment and mariner/pilot observation errors. Basically, the information available from radar is similar to that available from buoys, and can be similarly modeled. Radar and perception errors are considerably different, but the information needed to quantify these errors is readily available from previous SCI (Vt) studies. Generally, the position (state) estimates available from radar can be incorporated into the model as a third information source (i.e. in addition to the "primary" and "secondary" sources already considered). Logic will then be added to account for when, and

under what circumstances, radar is used by the pilot. This will permit radar to be modeled both as a backup (redundant) information source and as a primary source (as in poor visibility).

(2) Incorporation of Radio Aids to Navigation.
Incorporation of radio aids will be accomplished by identifying several typical, or potential, types of radio aid displays. For a given type of display, the modeling technique can be readily identified (such as can be done for radar, for example). Given that the model can accommodate various displays, then numerous variations in radio aids can be evaluated merely by identifying a candidate display and the error statistics associated with both the external system (signal source) and the receiver/display system. Variations in the errors induced by geometry which occur during a transit can be identified "off-line"; model input options will exist to permit incorporation of geometry sensitive errors. This modeling approach will be used because the model will then not be constrained to specific candidate radio aids, but rather only to on-board displays. Numerous radio aids exist, but on-board displays can be more standardized. The model will therefore be less subject to obsolescence and continual revision.

(3) Incorporation of Another Vessel as a Position Reference Input (for Passing Situations).
The ability of vessels to safely overtake or pass head-on in a channel is of particular importance in channel design and aids to navigation configuration. Under passing situations, mariners receive excellent relative position information from the other vessel. The simulation will be augmented to account for this by modeling the other vessel as a moving visual aid.

(4) Incorporation of "Optional" Mariner Types.
Logically, variations exist among mariners, and not all mariners can be modeled within any reasonable time and resource constraints. However, several basic types of mariners will be addressed. Of particular importance is the difference between pilots and masters, and their performance on various size vessels. Variations in mariners are currently being modeled to some degree by the amount of random variables (noise, etc.) incorporated in the model structure. Additional variation due to mariner type will be accommodated by identifying changes in the existing model parameters (anticipated errors, control loop gains, etc.). These changes will be incorporated into the model in terms of "optional mariners" so that the model user

will not be required to identify parameter changes, nor even understand the particular significance of each (other than at a general level).

(5) Augmentation of Modeling Details.
Numerous refinements of the details of the modeling techniques will be made. Each of these, in themselves, is straightforward and fairly insignificant. Further, the necessity for detailed model changes and the extent of modification required will, to a great extent, be identified as part of the validation activities (as is discussed in Section 3.6.3). Potential areas of model modification are mentioned here only to point out the areas wherein noticeable simplifications were made in the current model which are expected to be remedied in Phase II. These modifications include: (a) mariner mobility on the bridge (parallax), (b) buoy size and light intensity, (c) variations in USCG range design, (d) height of eye, (e) partial visibility, (f) error models (nonlinear errors).

3.6.1.3 Decision and Control Submodels

(1) The current PON model implements two strategic decisions: return-to-track and negotiate a bend. Additional strategic maneuvers that will be investigated include: making a series of small turns in an extended bend, entering a channel, entering or passing an anchorage, routinely meeting or passing another vessel, and compensating for changing cross-current and wind effects. To the extent that these decision strategies are important, with respect to the use and effect of aids to navigation, the model will be extended to accommodate them.

(2) Several tactical events can occur in a channel which should be simulated by the PON model. These include: approaching the channel boundary and approaching an obstacle. Tactical decision logic to account for these occurrences will be developed.

(3) The effects of the pilot's state estimation uncertainty need to be factored into his decision-making ability. This uncertainty affects the pilot's ability to choose the correct maneuver solution, where and at what time to apply various rudder deflections, and what magnitude of controls (rudder and throttle) are required. Also, the state estimate uncertainty affects the pilot's

anxiety and attention level, the extent that he relies on his radar, and the rate at which he changes his commands.

(4) Pilot decision-making steps with regard to radar and other electronic situation displays, and radio aids (such as Loran) will be added, as necessary.

(5) The impact of considering alternative "mariner types" may necessitate alternative choices of maneuvers; these will be incorporated as necessary.

(6) The commanded maneuvers used in the present study have been deterministic in nature. For example, fixed gains are used in the control laws for return-to-track maneuvers. However, the pilot will not always solve the same strategic or tactical problem in the same way with the same control sequence. There will be an even greater variance between various pilots. It may be appropriate to incorporate stochastic characteristics into the maneuver command logic.

(7) Logic to permit commands for speed control will be added to the pilot model.

(8) The pilot and helmsman model structure will be expanded to include the effects of heavy seas (marked vessel lateral/vertical motion) and limited visibility. The gains in the resulting control model will be adjusted to produce the average helmsman performance.

(9) The helmsman model will be modified to include stochastic effects. These effects include the uncertainty of the helmsman of his estimates and how these uncertainties govern his subsequent steering action. The randomness in the helmsman's steering actions will also be included.

3.6.1.4 Vessel Dynamics and Characteristics

(1) Hydrodynamic coefficients will be obtained for at least two and possibly up to five more vessels (besides the 80,000 ton tanker). These will be used in the vessel dynamics to ensure that the model results cover the spectrum of user possibilities.

(2) The dimensions of the various vessels will also be factored into the models as required. These may include effects such as bridge location and dimensions (for height-of-eye and pilot movement within the bridge),

vessel hull shape (for aerodynamic effects and channel boundary proximity measures), draft (for shallow water effects), and cargo loading (aerodynamic and hydrodynamic modifications).

(3) The throttle dynamics with engine response and vessel speed will be added. The effects of bow thrusters will also be added, if required.

(4) Other dynamic effects such as sea state (wave) forces on the vessel transient motion and bank suction forces will be added as necessary.

3.6.1.5 Additional Effort in Development of the Overall PON Simulation Structure

Additional effort regarding the overall simulation structure consists almost entirely of modifications which are necessary in order to support the additional capabilities of the submodels. All of these changes can be inferred from the preceding discussions. For example, in order to permit the pilot model to properly perceive another vessel and react accordingly, the simulation must be augmented in order to "drive" another vessel. Similarly, wind and sea states must be "generated."

The only PON modification activity which will be performed which does not stem from submodel modifications will be for the purpose of minimizing run time. The model currently runs at 2% of real time (on the UNIVAC 1108). This is considered remarkably good, in view of the fact that no specific effort has been made to reduce run time. Generally, careful review of the model computation sequence, on a simulation of this size, can permit reduction of run time by a factor of three to five. Such an effort will be undertaken in Phase II. While the run time savings will be somewhat offset by increased model complexity, run times from .5% to 1% of real time are fully expected.

3.6.2 Data Base Expansion

The navigation data base established for Phase I contained sufficient information to establish the essential elements of the Process of Navigation; this, in turn, enabled initial model development. The data base was also sufficiently broad to enable Phase II to commence in a timely fashion. However, as the content, format, programming, and testing of the model began to take shape, areas of additional desired information were realized. While much of this information may require experimentation to quantify the parameters; others may be acquired through the same process used in establishing the original data base. In addition, because Phase II will commence with numerous model runs, additional unknowns or areas of required expansion will become apparent early in the work effort.

This section of the report is devoted to the presently known areas where the data base requires expansion, without explicitly defining how the actual data will be collected.

3.6.2.1 Vessel Characteristics

The vessels which can presently be utilized in the model are those which have known hydrodynamic coefficients. These vessels are also the same as presently used in the research facilities, which may be utilized for model verification or collection of data which is presently not quantified. Unfortunately, the data available on vessel characteristics covers only a small number of vessels, most of which are in the "new" category. In the development of establishment/disestablishment criteria, the aid configuration must be capable of providing safe navigation capability for all vessels, not just those tested in a research facility. Thus, vessel characteristics are needed for what the pilot describes as "animals," which are older and probably less maneuverable. This need for the data base expansion is verified by the accident data which

AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7

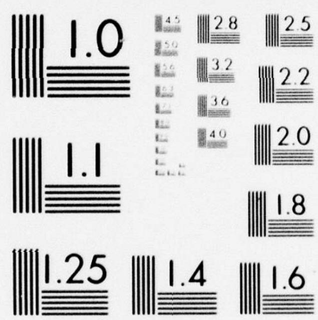
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)

MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A

UNCLASSIFIED USCG-D-38-78 NL

3 OF 6

AD
A059891



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

revealed that older vessels were as prone to accidents as newer vessels, despite their smaller size. Also, the interviews with mariners stressed the need for an aid configuration compatible with all types of vessels.

The data base expansion of vessel characteristics should also contain more information about wind effects. Of particular interest is the effect of the bow passing through the wind, and the effects on shear rates during this transition. Additional data on shallow water influences are also desired.

3.6.2.2 Mariner Characteristics

During the interview process, several instances arose where inferences could be drawn that different people perform the Process of Navigation in a slightly different fashion than would be considered the norm. The Coast Guard/MARAD data from CAORF also indicated that some pilots' estimates either had larger errors or variations from the norm. Additional data should be collected to ensure that these mariners are included in the data base so that the error variances represent a more realistic sample of the real world.

As the model tests are conducted, areas of further expansion of input requirements will be developed. Some of these will influence the details of expert interviews. Thus the data base derived from the interviews will necessitate a repeat of the general interview process utilized in Phase I.

3.6.2.3 Aids to Navigation Errors

For Phase I, the model has been programmed with all aids considered as fixed buoys (or beacons). To incorporate real world parameters, the buoy models must include their attendant watch circle errors. This will require a relatively simple analysis

of the types of aids and mooring conventionally used, the depth of water, scope of chain, etc.,and the resulting watch circle errors. While these errors may be small relative to the overall errors in the process of navigation, their inclusion in the model is necessary for ultimate mariner acceptance of a model-based system implementation plan.

Placement errors are not critical to the exercise of the model, since this can be an operator input. However, any information derived from ongoing Coast Guard studies of aid placement errors will be useful in determining the operator input offset values.

3.6.2.4 Height of Eye, Bridge Location

The model requires testing to ascertain whether or not the height of the observer's eye has any effect on the process of navigation performance. If the results indicate that this is a sensitive element, the vessel characteristics data bank will require expansion to incorporate bridge height and the range of height from a loaded to a light draft. In a similar fashion, the location of the bridge fore, aft, or amidships may have some influence on the navigation process, and may require inclusion in the model.

3.6.2.5 Accuracy Requirements

The theoretical bounds of accuracy are needed to develop a systems requirements analysis. Since this is dependent on the mariner's perceived limit or crab angle for various situations, expansion of the data base is required.

3.6.2.6 Accident Analysis

The amount of effort required to permit internal model derivation of an accurate accident probability estimate is too high to be productive. As a result, the model performance measures relating to accident probability will be calibrated with real data. The accident review conducted for Phase I requires reassessment to ascertain better descriptors of the conditions encountered which may have led to the accident. This would encompass identification of current and wind vectors with respect to channel alignment, special harbor module configurations, etc.

3.6.2.7 Aid Configurations

To examine the full scope of establishment/disestablishment criteria, the model should be tested on a large variety of aid configurations. A starting point for these tests are configurations presently in existence in major ports of the U.S. This requires a detailed examination of charts for these ports, a compilation of harbor module and aid configurations, and a summary of common items. Table 3.9 is a sample of the areas for consideration, but does not include the detail necessary for model testing.

3.6.2.8 Local Practices

Many local practices have been established by masters and pilots to enhance safety. A collection of these practices, concurrent with the collection of harbor module and aid configuration data, would be helpful in testing the model. This would not only enable testing of these practices, but if the practices are verified in the model, it would assist in mariner acceptance of the study.

Table 3.9

Channel Samples, US East and Gulf Coasts

LOCATION	FROM	BEND	TO	WIDTH	DEPTH	NOTES
Savannah	Tybee Range	30°R		600	40	Followed closely by 40° bend.
Tampa Bay	Cut A	45 L	Cut C	400	34	Staggered and gated in, Staggered out
Galveston	Inner Bar	30 R	Bolivar Road	800	42	
New York	Sandy Hook E.	45 R	Sandy Hook	800	35	Gated in and out, large truncation
New York	Sandy Hook	45 R	Raritan Bay East	800	40	Mixed in, one side out
Delaware	Liston Upper	35 R	Baker	800	40	Mixed in and out
Baltimore	Craghill Upper	35 L	Brewerton	800	42	Gated in and out

3.6.3 Model Validation

This section addresses the methodology to be used for the validation process in Phase II. Some insight and guidance can be gained by considering previous research activities in this area; this is discussed in Section 3.6.3.2. The sensitivity analysis and experimentation plan is discussed in Section 3.6.3.3. Finally, experimental design considerations are presented in Section 3.6.3.4, including human factors, measurements and data collection.

The implementation of a specific experiment requires the following major tasks.

(1) Establish required objectives/hypotheses

(2) Determine appropriate facility to obtain desired objective

(3) Design experiment operating scenarios to include:

- channel/aid configuration
- type of vessel

- environmental condition (fog, day/night, cross current, etc.)
- subject mariner considerations (type, numbers, frequency of runs, etc.)

(4) Detailed planning and preparation

- mariner selection and education process
- data collection procedures (devices - tapes, interviews - frequency and method of collection)
- scheduling of runs
- set up of the test facility

(5) Run experiment/collect data

(6) Analyze data and iterate (when required) starting with item (1)

3.6.3.1 Methodology

A carefully designed model validation procedure will be followed to ensure that the Process of Navigation model and the Navigation System Evaluation procedure utilizing this model will produce performance measures that are valid and useful to the Coast Guard in assessing navigation aid needs. The methods followed in validating the model structure and fidelity of its output are closely related to the procedure to further develop the model and expand the data base discussed previously. Thus, this procedure will go on simultaneously with the expansion of the model. For example, an experiment may be run to determine values of parameters in the pilot command function (control laws) discussed in Appendix F. In the process of running this experiment, it may be discovered that a better agreement will exist between the experimental data and the model predictions if another term is added to the control laws. The extra term would then be added, and the values of the parameters would be adjusted to give a good match between what the computer model predicts and what the experimental results indicate. In this

way, the model is expanded and adjusted to reflect a closer approximation of reality. In addition, the model is validated because its subsequent predictions match those obtained from the carefully controlled experiments.

The model validation procedure will draw on the entire data base, if required. Accident data, actual sea trials, and results of mariner interviews will indicate areas requiring model validation. Perhaps the most important data, in this regard, will be obtained from various manned simulation facilities, the most important of these being CAORF. Specific facilities are discussed in Section 3.6.3.4.

The methods followed to validate the model can be categorized into three different activities, as follows:

(1) model sensitivity analysis

(2) model extensions

(3) validation via experimentation

Each of these items is now described in detail.

3.6.3.1.1 Model sensitivity analyses

In one sense, this is the procedure by which the Process of Navigation model is repeatedly run over an example scenario. The purpose of this type of sensitivity analysis is to exercise the model with various parameter values to determine (a) what the important parameters are in the model, (b) what to look for and how to structure the experiments, and (c) what is the specific relationship which exists between each of the important model parameters and the specific outcomes obtained by running the model. An example of this sensitivity analysis for the decision and command functions for the model is described in Section 3.4.3 and Appendix D. For each computer run, all but one of the parameters

are set at baseline values. One parameter is set at various values to evaluate its effect on the outcome of the model. As an example, one specific outcome of this analysis is the sensitivity of the cross track deviation error produced by the helmsman as a function of compass noise. Another example is the sensitivity of cross track deviation error produced by the pilot as a function of the distance between pairs of buoy gates. If the outcome is quite sensitive, then this model parameter must be accurately known. Experiments must be run to ensure that the model structure and parameter values are correct. Alternately, if the results of a sensitivity study show that the variations of a parameter has little effect on the model output predictions, then this parameter is judged as unimportant. Consequently, its value can be set at some reasonable value and experiments need not be run to validate it.

3.6.3.1.2 New functions and effects

As the model is expanded, the structural relationship between inputs, model parameters, and outputs may change. Whenever the model is changed, new sensitivity runs might be required to ensure that the overall model continues to be valid over the spectrum of possible scenarios it will be required to evaluate. If model changes produce changes in previously validated results, then the model parameters will have to be adjusted so that the same desired results are achieved. This process may also result in additional experiments to verify the validity of the model.

One example of this would be the extension to the state estimator portion of the model to account for loss of visibility due to fog. This will result in a larger uncertainty in the pilot's estimates of the vessel state. This increase in uncertainty may cause the model to indicate an increase in number of groundings which is greater in number than what is experienced in actual

fog conditions. An investigation of these conditions may reveal that when pilot experiences fog, he requires more cautious position fixing, and relies on his radar to confirm what he thinks he sees from the buoys. These changes would have to be modeled and included in the Process of Navigation model to counteract some of the effect of the fog. Adjustments to the overall model would have to be made until results obtained from the experiments are matched.

3.6.3.1.3 Validation via experimentation

Two previous activities mostly involve running the model and adjusting the model to determine important sensitivities. This final activity involves running experiments of various levels of complexity at various facilities to confirm the outcome predicted by the model. Whereas the model can be run at an unbounded number of points in the spectrum of scenarios at relatively low cost, the simulation experiments are limited because of cost constraints and limitations of experiment facility capability. Therefore, these experiments must be carefully planned and chosen to verify the fidelity of the model at selected points in its operating spectrum.

The experiments have the purposes of (a) verifying that the results of the sensitivity analyses are correct, (b) discovering new phenomena that need to be incorporated into the model, (c) determining values of key model parameters and how they change with a changing scenario, (d) spot checking the validity of the model's predicted outcome (performance measures) at specific operation points, and (e) ensuring that the concept of utilizing a systems approach in the development of the PON model produces results that would have been obtained by running several elaborate experiments in the real world.

It is emphasized again that the PON model needs only to be validated in the sense that for the modeled scenario, it produces the same outputs as would be obtained in the real world. That is, for a given situation, the model should predict the correct vessel state error statistics, pilot workload, effectiveness of his steering commands, levels of stress, and helmsman effectiveness. There is no need for the model to be isomorphic to human operator models predicted by another technology, nor it is necessary for the model to predict vessel outcome in situations where aids to navigation are not used or have little effect on the outcome (such as a collision avoidance maneuver).

One form of "experimental sensitivity analysis" is the process whereby, during an experiment, a single variable is changed to see its effect on the outcome. For example, in a wheelhouse simulator (such as CAORF), the cross-track position can be changed at a given location along the channel to determine the pilot's estimate of cross-track position. The position of the buoy pair downstream may be varied to evaluate its impact on the pilot's estimates of his along-track position. This type of static error (quantified by mean and standard deviation) is a function of actual vessel position in the channel. These statistical quantities are then used to set values of parameters in the model as well as the model structure.

Another type of manned experiment which can be performed is available from aircraft simulators. One common technique used in aircraft pilot training is to show the individual his performance at the end of his run. In these experiments, the attempt is to speed up the learning process by providing positive reinforcement. This idea can be useful for CAORF-type experiments. The attempt would <u>not</u> be to improve mariner's learning capability, but rather to provide additional navigation aid placement information. The procedure might be as follows: A mariner makes a transit with a fixed buoy configuration. His track is shown to him after completion of his task. He is then asked what additional aid

locations would help improve his performance. An additional transit would then be performed with these additional aids, and comparisons would be made to previous run results. The philosophy behind such an experiment is twofold. First, the (hopefully) improved performance can be observed and, as such, represents a sensitivity type experiment, as previously discussed. Second, this gives some indication of the mariner's perception of his performance as compared to his actual performance and the various control strategies going into each.

3.6.3.2 Previous Validation Efforts in Human Operator Technology

Previous research and model validation efforts directly analogous to the current study concerns driver steering control models, and helmsman steering models for ship maneuvering at Delft University, The Netherlands. Details concerning this research are discussed in Appendix E, and its relevance to the aids to navigation validation task is considered.

The driver steering control models contain aspects of human performance equivalent to the tasks required of the mariner. The driver is required to view an ever-changing scene, estimate relevant system parameters and apply various decisions and control strategies to effect "adequate" system performance.

While the helmsman steering models are rather specific to tasks limited in scope, the methodology employed in developing and validating these models are similar. In both areas of research, human operator models were developed within an overall system simulation. These models were sufficiently exercised to obtain insight into their characteristics, functional relationships and input to output structure. A hierarchy of models was developed specific to functions of the operator pertinent to his particular intention. These operator relationships with the system dynamics, environment and scene geometry were validated

utilizing appropriate simulation facilities. Thus, the model structure itself implied certain relationships that could be validated to any sufficient degree, primarily limited by time and cost considerations.

3.6.3.3 Experimental Sensitivity Analyses

Four levels of variation can be made to the Process of Navigation model for a sensitivity analysis. Examples of each are as follows:

(1) Model parameters - Example: the gains used to characterize the manner in which the pilot brings the vessel back to the desired track when he perceives that the vessel state is in error.

(2) Model threshold - Example: the magnitude of the allowed cross track deviation before control is resumed from the helmsman in a situation where the current is continually changing.

(3) Model structure - Example: the manner in which the pilot's perceived uncertainty of the vessel's state affects the way course changes are commanded.

(4) Model logic - Example: the simulated process of the pilot turning over control to the helmsman upon entering a straight portion of the channel.

Each of these levels is varied during model construction in a trial-and-error manner, in obtaining a model producing a "desired" outcome. After the model's qualitative characteristics are well known, variations are made to the parameters and thresholds to tune the model and to aid in designing meaningful and efficient experiments.

In constructing the PON model and verifying its fidelity, it is useful to consider the model as a hierarchy of functions. An example of this hierarchy is shown in Figure 3.52, with the state estimator function shown in more detail. At the top level, the Process of Navigation model is used in a Monte Carlo procedure

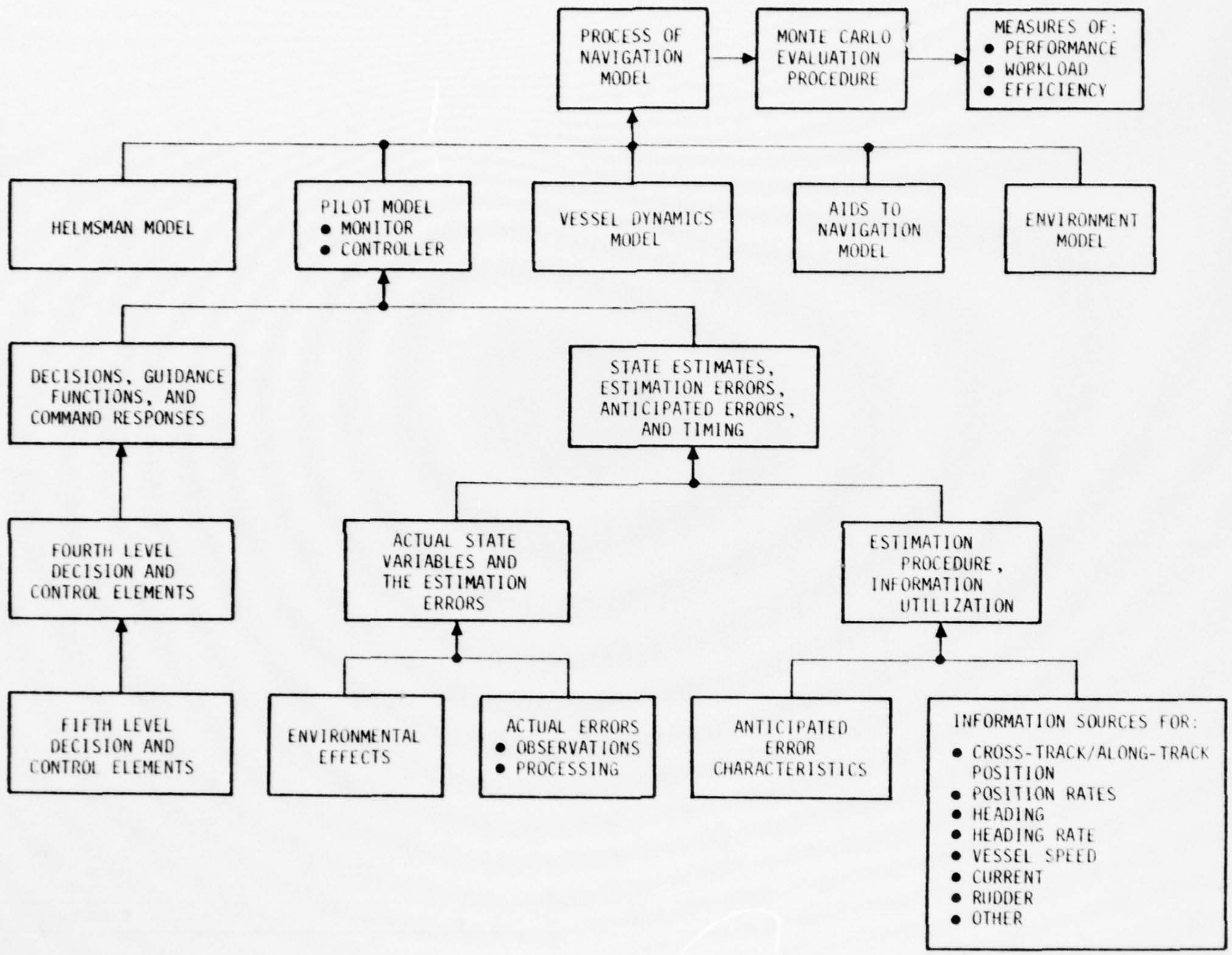


Figure 3.52 Hierarchy of Process of Navigation Model Structure

to obtain meaningful measures of navigation performance, workload, and efficiency. The next level consists of the main sub-blocks of the model - the pilot, helmsman, vessel dynamics, aids to navigation, and environment models. The level under the pilot model consists of the state estimator model as well as the decision maker and commander models. The level under the state estimator portion of the model consists of the modeled estimation procedure, and a model of the estimation errors. The bottom level of the model contains the most basic elements comprising the system. For example, one basic element consists of the position of a single buoy; the position of a single buoy produces a range fix and an angle off the bow.

In constructing the model, one must identify the elements of each block in the hierarchy and the exact interconnections that relate each of the blocks. In validating the model by way of experiment, one must determine the most appropriate facility and its required use to verify the elements in each block. The model becomes more complex as it rises in level of the hierarchy. Thus, more complicated facilities and experiments are required to fill in the block at a higher level. In experiment design there is a tradeoff between running several simple experiments at a lower level or a single, more complicated experiment at a higher level to identify and validate the model. The experiment design decisions must be based on determining the most efficient way in which to assess this overall model structure in providing the required level of model fidelity. In general, for a given block of the model hierarchy, the simplest possible experiment facility should be used.

As mentioned before, in choosing what experiments to conduct, the first step is to identify what elements of the model are most critical to the performance measures to be obtained.

Appendix H contains a description of sensitivity analyses that were made using the current PON model to determine the relative importance of the parameters that make up the control laws in the pilot decision maker and commander functions. From these analyses, the following conclusions were made:

(1) The amount of preview time used by the pilot to project his future state is critical in that it governs which steering control strategy is used at the current time. A large preview time can cause use of the wrong control strategy. Conversely, too small a time will produce control inefficiency and increased workload.

(2) The amount of damping used by the pilot to remove unwanted heading rate is important. Too low a value will produce too much workload (large amounts of overshoot).

(3) The quantization levels used by the pilot to command the rudder angles must be related to the state error thresholds.

(4) The error thresholds used by the pilot must be a function of vessel speed and width of the channel.

These conclusions can be directly used to formulate experiments to determine appropriate model parameters, thresholds, and structure required to produce the expected performance measures. For example, in identifying an appropriate damping factor for the pilot, an experiment could be conducted whereby the vessel is displaced from the centerline with various heading errors. The test subject would then be instructed to return the vessel to the centerline. By observing and recording the subsequent vessel motion and commanded rudder action, the corrective path with its associated workload could be determined. The model control law, with its damping term and levels of quantization, could be adjusted so that the same statistical performance levels would be generated (in terms of vessel state error vs. time and rudder deflection (a measure of workload) changes vs. time).

An example of how the experimentation process will be used to generate sensitivity numbers as well as model structure is pointed out by preliminary results obtained from recent restricted waterways experiments run at the CAORF facility [3]. In this experiment, nine guest pilots were placed in various cross track positions at two points along the channel as shown in Figure 3.53. In the first along-track position (Pos D&F), the pilot is 1820 ft. from the first gated pair of buoys, and in the second position (Pos E and G) the pilot is 4860 ft. from these buoys. Positions D and E are nominally centered on the lower left boundary of the channel and varied around this location in 3 foot increments for a total variation of ±18 feet. Positions F and G, are nominally located in the center of the channel and varied about this location in 9 foot increments out to ±54 feet from the channel centerline.

Figure 3.54 shows the computed standard deviation in the pilots' estimate of the cross track deviation as a function of the actual cross track deviation. (The abscissa-actual cross track deviation is referenced from the nominal location.) Zero deviation for locations D and E refer to the left boundary of the channel; in the case of locations F and G, zero deviation refers to the centerline of the channel. For locations D and E, the estimation error at first grows linearly with the actual cross track deviation. After the actual deviation reaches about 20-30 feet, this deviation seems to level off. This linear function is quite apparent, in particular from Figure 3.54 for Position E. This linear function relating errors versus cross track deviation for locations D and E is primarily due to the fact that the mariners were ranging on the buoys located at the left boundary. In contrast, cross track information obtained at locations F and G are obtained from angle differences from the two pairs of buoys and as such, the errors are relatively independent of channel location. Also note that the error data indicates

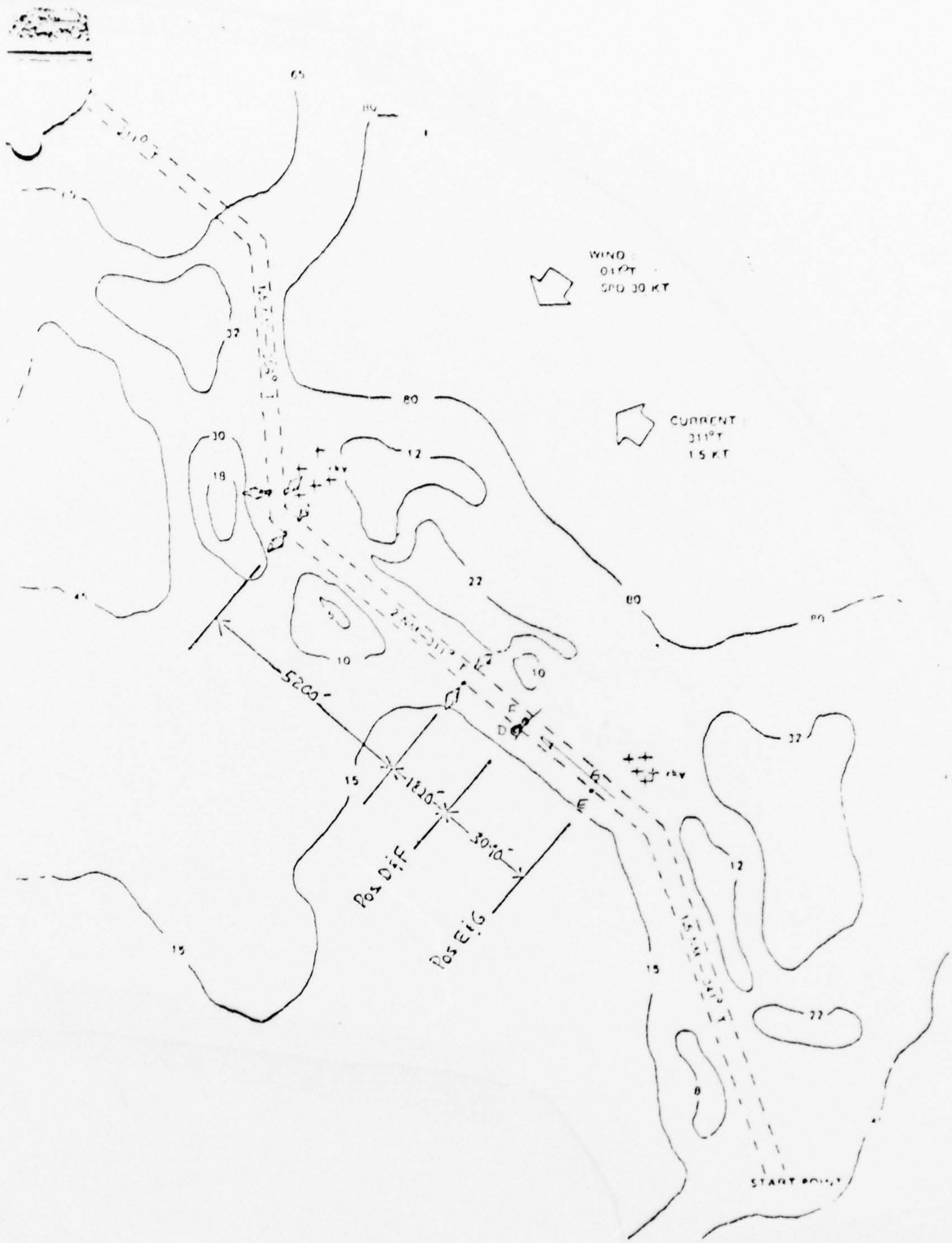


Figure 3.53 Channel Design for Cross-Track Deviation Estimation Experiment

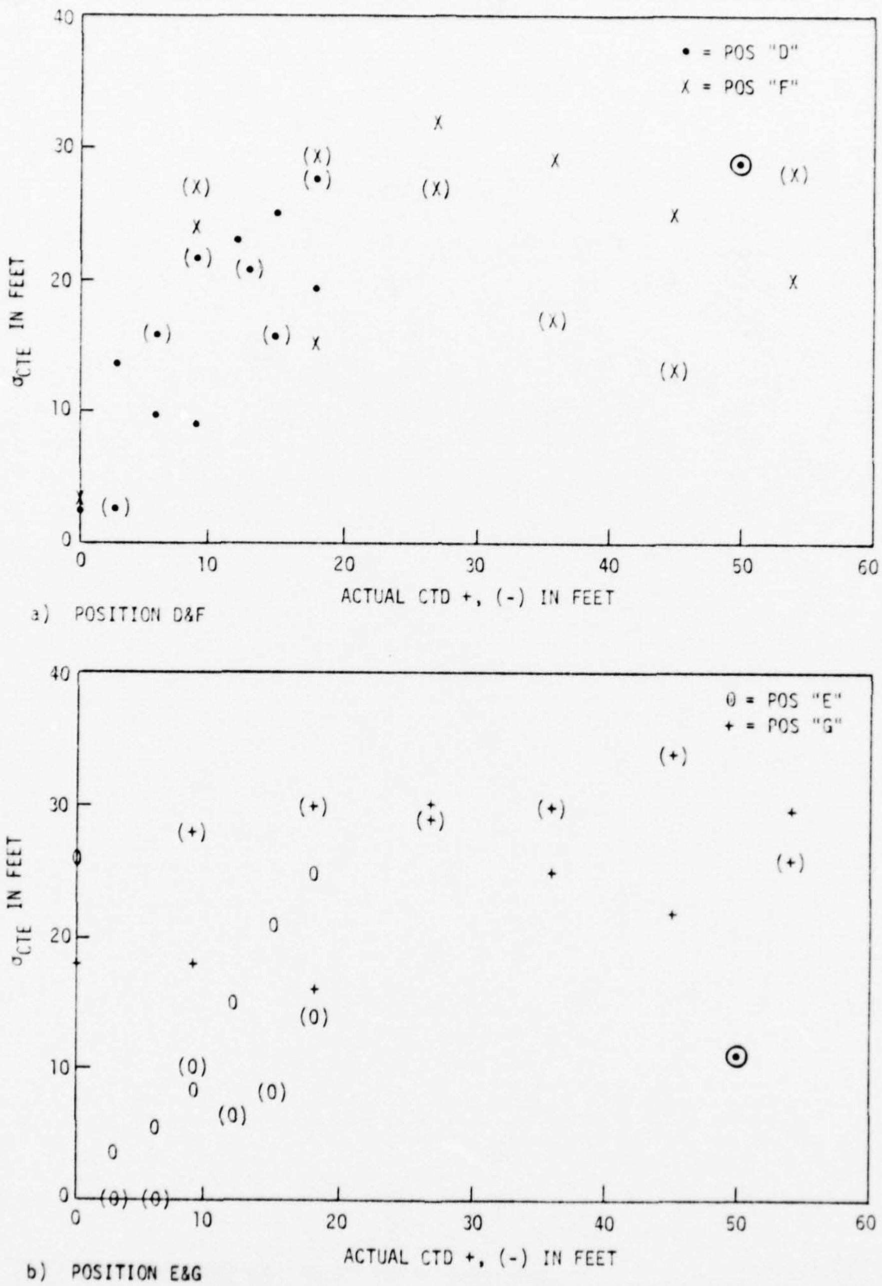


Figure 3.54 Channel Cross-Track Estimation Error Statistics as a Function of Cross-Track Position

asymmetry in sign perhaps due to conflicting buoy location information immediately beyond the turn. This data supports a hypothesis that extremely accurate cross track information is obtainable by observing differences of angles between buoys.

This type of experiment reveals the structure of the model describing the pilot's cross track estimation error for when he is obtaining position information from a range and from two gated pairs of buoys. The results of the experiment can be used to identify certain selected model parameters.

3.6.3.4 Experimental Design

In planning the experiments, it is important to keep in mind all the types of experiment facilities that are available for obtaining information. The experiment designer will map each element of the model structure to a facility where he will identify the element model or verify that the existing model is correct. The types of facilities available include:

(1) Psycho-physical experiments - set up where human perception levels can be tested (e.g. the ability to distinguish the angle between two adjacent objects).

(2) Previous similar or analogous experiments - for example: Ref. 4 - conducted to obtain the typical response of the helmsman in the presence of disturbances from high seas. Ref. 5 - conducted to obtain the deterioration of a human driver's estimation ability in the presence of limited visibility.

(3) Actual piloted vessels leaving and entering harbors - from observations and interviews, one could determine a great deal about typical workload levels, the state estimation process, the decision making process, and other factors governing the overall Process of Navigation.

(4) CRT type simulator - such a system is easy to construct and it could be used to obtain much of the dynamic information that can be obtained from more expensive wheelhouse simulators.

(5) Wheelhouse simulators - CAORF is the primary example. Such a facility provides the ultimate way of determining information from a controlled experiment with men in the loop. This type of facility should be used to test the performance of the overall PON model predictions at key points in the operating scenario. Its primary purpose should be validation of the model results rather than design of the model itself.

The use of any simulation facility requires consideration of the experiment's objectives, the human factor variables, and the selection and recording of experimental variables. The first requirement is to clearly establish experimental objectives. These should be defined as precisely as possible, prior to experimentation. In practice, however, this results in an iterative loop, preliminary runs are made, and changes in the numbers and types of configurations are made as an outgrowth of previous results. This puts an added time constraint on the available simulation facility. It is SCI (Vt)'s experience, in setting up previous simulation validation experiments, that potential problems arise if too many objectives are designed in "piggyback." This is particularly true when psycho-physical data is to be collected for human factors/man-machine interface objectives, versus modeling validation efforts where the focus is on determining causality of various system variables. Tradeoffs are required to maximize useful outputs to address these sometimes conflicting requirements.

It is for this reason that SCI (Vt) recommends the use of a small scale CRT simulation facility to minimize resources in developing an experimental design. This facility can also be used in establishing functional relationships and model parameters that are appropriate to the micro level validation of the PON.

Human factor considerations in experiments must ultimately address the form and type of analyses to be performed on the resultant data. These considerations refer to such aspects as subject-to-subject variability and a methodology to deal with this. Models for the estimator, decision, and commander functions in the mariner rely on stochastic (random) disturbances which can be varied to reproduce both the adaptability and variability inherent in human performance. Adequate experiment design must focus on the random nature of mariner performance.

There are two general types of analyses that can be performed on experimentally produced data. The first is of a subjective nature and relies on analyzing individual runs to note trends, biases, and anomalies in the data. In many simulations where experiments are extremely costly or time consuming, this might be all that can be performed. The second type of analysis is statistical in nature; analysis of variance techniques and repeatable statistical independence are examples. Human factors must be considered to the extent that repeatability, sufficient statistical independence and subject-to-subject variability is minimized.

Experimenters have developed a technology to address these issues. Random ordering should always be used to minimize the operator's "learning" of the experiment to such an extent that biased results are obtained. Where repeated trials are to be performed with different parameters, a proper mix of mariners and experiments is required. Sufficient numbers and levels of experienced mariners must be used to obtain statistical confidence in extrapolating results to other situations. Other deliberate attempts to obtain unbiased results must be used. Instructions, preliminary briefings, and data collection techniques utilizing post experiment interviews should all be standardized.

Several types of measurements can be collected during an experiment for subsequent processing. The first type involves closed-loop system performance measures. These include such variables as cross track/along tack location, heading/heading rate, etc., all collected with associated time marks. Another type is mariner output: rudder calls, helmsman rudder commands, heading changes, and speed changes. A third category is specific to workload measures. For example, the time and magnitude of rudder calls to the helmsman should be correlated with the scenario geometry so as to provide an indication of increased stress and level of activity as a function of aid placement within the geometry. This type of data would be necessary to identify changes of strategy in negotiating turns and passing other vessels. Changes in this type of output versus variations in channel configuration will also provide meaningful workload measures that can be validated in the PON.

Mariner behavior should be observed by psychologists in an attempt to correlate increased stress levels with mariner performance. CAORF would be the most obvious faciility to record such data. Post mission interviews would be the last step in the data collection phase, These interviews can be either oral or written, or both.

3.6.4 Navigation System Evaluation

As the Phase II model nears completion, there will be a need to test the model for conditions which approximate the real world. This testing would be accomplished prior to any final validation efforts which would be performed at a CAORF type research facility. These near-final tests would encompass all of the material necessary

to achieve the Phase II objectives, including vessel safety and traffic facilitation, and establishment/disestablishment criteria. This assumes that many prior experiments and tests concerning subtotal areas have been completed.

The purpose of this evaluation is twofold. The first is to validate all of the model parameters collectively, and the second is to demonstrate the achievability of the Phase II objectives. Inherent in the Phase II objectives, whether stated or implied, is ultimate acceptance by the mariner of changes in an aid configuration which have been derived on the basis of model execution. The latter may be the most important reason for the evaluation.

Because of this potentially close tie to mariner acceptance, the manner of navigation system evaluation must be carefully structured. It would include, as a minimum, the following concepts:

(1) Incrementally progressive disestablishment criteria

(2) Consonance with predeveloped mariner concepts

(3) Use of real world situations as examples

There is little doubt that mariners will accept the criteria developed to add a single or small number of aids to an existing configuration. Interviews with mariners and with Coast Guard personnel indicate that this is a common practice today, albeit lacking a model which demonstrates the effectiveness of the change. Where major new waterways have been aid-configured, it has been an incremental process, with each step essentially requiring mariner approval.

The disestablishment of aids is a much more difficult task even for a single aid. Frequently the history of its original establishment rationale is not available. Special interest groups may be involved but not known. Time consuming hearings may be needed, with the final criteria being based on a collection of opinions and conjectures.

Since there is no reason to believe that the political problems involved in configuration management will change, the modeling in Phase II must be sensitive to these conditions. In essence, this means that when a final configuration has been determined and tested in the model, it must include the incremental changes which may be required prior to the final configuration.

Mariners have preconceived ideas concerning where aids should be located, whether they can be lighted or unlighted, etc. These ideas have been developed over years of experience and learned behavior. However, our information indicates that a great amount of this is biased by the location, i.e., pilots in one port have been trained by their superiors and thus reproduce their thoughts. This does not imply that these ideas are in error, but may indicate that there will be differences between major ports. If the results of the study indicate that aid reconfigurations are possible, these preconceived concepts may require alteration. Again, an incremental implementation is probably the approach to be taken. This may be enhanced by the specific port comments which could lead to the swapping of aids and/or the initial disestablishment of aids which have been cited as acceptable by the port pilots.

Because there is a diverse configuration of aids for existing channels within the U.S., there is a high probability that an optimum configuration determined by the model will closely match one of these existing configurations. Since a portion of the Phase II effort will be devoted to collecting information on these channels, the match can be expected with only a small amount of effort.

If a match is found, an in-depth examination of all situations incorporated into this configuration would be conducted. This would include interviews with the users and managers, determination of the vessels using the waterway, local customs or procedures, and the normal and abnormal situation modifiers. Information developed in this examination would then be implemented in the model to show

the performance of vessels and determination of the vessel safety and traffic facilitation parameters.

With the final correlation completed, the outputs would then be an excellent example of the model's capability, and could be used to promote mariner acceptance. If necessary, a final demonstration on a CAORF type facility, using the mariners from the specific port, could be used to further promote mariner acceptance.

3.6.5 Facility Development

3.6.5.1 User Interface Methods

User interface with the Navigation System Evaluation Model involves the transmitting and receiving of two types of information:

(1) Alphanumeric (textual) -- e.g. inputs which select model options or specify situation modifiers, or output numbers which summarize performance*; and

(2) Graphical -- e.g. inputs which define harbor geometry or candidate buoy locations, or outputs which represent simulated vessel tracking histories.

Processing alphanumeric data is a routine function of modern computing systems. Such data may be transmitted or received by a variety of methods, the foremost of which are punched cards and CRT terminals. Convenient formats for the alphanumeric data serve to simplify the user's role in exercising the model and accessing its data base.

Graphical data presents more of a problem. If the data is to be processed in the "batch" mode, graphical input data must

* See Sections 3.3.2 and 3.3.4 for a description of model input and output requirements, respectively.

be digitized a priori. For example, the Phase I model reads the channel boundaries and desired track as a series of records, each of which defines an x and y position and a heading for a point on the particular line; the computer, in effect, connects these points internally in a prescribed manner.

Exercising the model in an "interactive" mode permits the utilization of some very useful technology designed to specifically address this problem. Modern graphics systems have a "controlled cursor" capability, where the user positions a display-generated symbol (the cursor) anywhere he desires on the screen using a "joy stick," "trackball," or other positioning device. He can thus position the cursor, enter the point by pressing dedicated button or a key on his keyboard, reposition the cursor and repeat. Another very useful device is the digitizing tablet, which consists of a back-lighted table and a hand-held scanning device. The user simply passes the device over a drawing, chart, or map which he wants to digitize, aligns the cross-hairs of the scanner with a point on the desired curve, and pushes a button. The data is automatically entered into the graphics system and displayed on the screen. The digitizing tablet has the distinct advantage that the user can work with a precise chart of the harbor element of interest; he does not have to rely on a sketch or point-by-point transcription of the chart, which frequently introduces human error. These modern graphical data entry methods are in wide use today, particularly in the fields of mechanical design, map-making, and industrial process control.

3.6.5.2 Computing Options

With a system of the sophistication level of the Navigation System Evaluation Model, two options exist for providing needed computing power:

(1) mainframe computer system

(2) minicomputer system.

Either of these can be accessed in batch or in an interactive mode using a standard CRT or a "smart-terminal" graphic system, i.e. one which has its own computing capability (usually microprocessor).

The minicomputer system has a distinct advantage over the mainframe for interactive processing where a "smart-terminal" graphics system is required, as follows. Most mainframe systems are general purpose computing facilities, accessible through standard lines to input/output devices. These communication mechanisms are, in general, restrictive to a smart-terminal graphics system, particularly if a quantity of data needs to be transferred between computer and graphics terminal. Minicomputer systems, on the other hand, are usually more accessible to the user, occasionally even dedicated to the interactive graphics system. In this case, high speed parallel interfaces can be installed, linking the smart-terminal with the minicomputer's memory and facilitating user interaction.

3.6.5.3 Recommended System

SCI (Vt) is interested in providing a Navigation System Evaluation Model of maximum utility to the Coast Guard. To achieve this, the model must be easy to use; it must generate results in a timely manner, and it must be cost effective in its implementation.

With these objectives in mind, and in view of the previous discussion, SCI (Vt) recommends that the model be implemented as an interactive tool, using a "smart-terminal" graphics system and, preferably, a high-performance minicomputer.

Figure 3.55 shows an "upper bound" on the sophistication of such an interactive system. The intelligent graphics system consists of a display terminal with alphanumeric keyboard, cursor control and sufficient memory. Optionally, the user station can support a digitizing tablet and hard-copy plotter. The system communicates with a computing system, preferably through dedicated lines. The model may also be accessed by remote sites (CAORF, contractor support facilities, etc.) by a communications network of voice grade lines.

SCI (Vt) regularly develops systems of the type shown in the figure for a variety of applications -- energy management, waste-water treatment, industrial process control. We are confident that the Phase II Navigation System Evaluation Model will be entirely consistent with such an implementation, and that the recommended system will provide maximum utility to the Coast Guard in a cost effective manner.

3.6.6 Software Design and Documentation

A substantial amount of software has already been developed in Phase I to implement and demonstrate the Navigation System Evaluation Model. The software is coded in standard FORTRAN so as to be transportable to the vast majority of minicomputers and mainframe computers in use today. The code is well "commented," and documented in various memoranda.

As discussed in Section 3.6.1, additional software development is planned for Phase II to implement the following:

(1) Model extensions or modifications

(2) "Stream-lining" the code for maximum efficiency

(3) Modifications to interface the user and model with particular computers.

All three of these items are minor in comparison with the development of the original model. Item 3 above -- user/computer interface -- is somewhat more involved if the model is to implemented

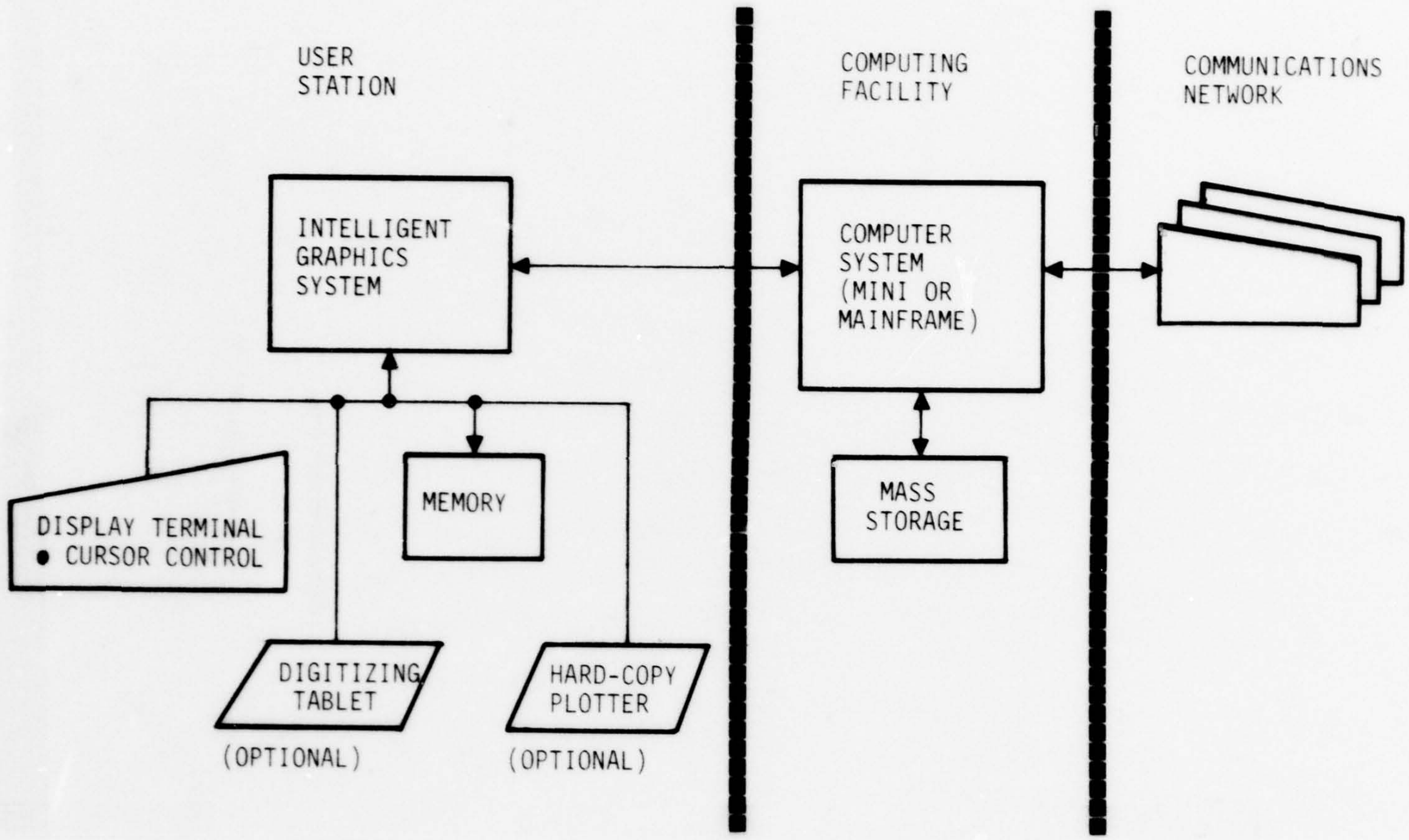


Figure 3.55 Potential Sophistication of User Interactive Navigation System Evaluation Model

in the real-time interactive mode, as recommended in Section 3.6.5. In this event, software must be written to support the interactive display function. This task has been greatly facilitated of late by the advent of microprocessor-based graphics systems, which employ special hardware and "firmware" (non-changeable software) for such tasks as character generation, vector generation, display scaling, and cursor control.

Whichever user interface form is selected, SCI (Vt) will establish the Phase II model on the selected computer system and provide supporting documentation in the form of:

(1) Commented listings of the model and support routines;

(2) Flow charts of all but the simplest subroutines; and

(3) A user's manual.

The model will be demonstrated for USCG acceptance, and USCG personnel will be instructed in its use.

IV. CONCLUSIONS

During the course of the Phase I effort, SCI (Vt) completed a survey of experts in navigation, navigation research, and aids to navigation system planning and summarized the current state-of-the-art in each area. The essential elements of the process of navigation were identified and were incorporated in a functioning model of the process of navigation. This model was used to successfully emulate mariner/vessel performance in real-world conditions. The mariner's requirements for navigational information were identified and the amount and type of navigational information available from aids were identified and correlated with information utilization associated with unique harbor, vessel, environmental, and visual aid system characteristics.

The form and structure of a preliminary Navigation System Evaluation Model was developed, and the requirements for model completion and validation were defined.

The foremost conclusion derived from the results of this study is that the application of fast-time simulation techniques to the evaluation of mariner/vessel performance is feasible and that it provides an overall framework for: (1) design of simulator and operational experiments, as well as the utilization of all experimental data effectively, (2) the assessment of Aids to Navigation System Requirements for a broad range of situations in an expeditious and cost effective manner, and (3) the determination of quantitative criteria for the establishment/disestablishment of systems of aids to navigation.

Detailed conclusions evolving from the results of the study are presented in the following sections; categorized under the headings of "State-of-the-Art," "The Process of Navigation," "Methodology for Navigation System Evaluation," and "Application of System Evaluation Methodology."

4.1 STATE-OF-THE-ART

- The primary conclusion concerning the state-of-the-art of the audio visual aids to navigation system is that methods for quantitative analysis of integrated aid to navigation systems, or quantifiable parameters defining the process of navigation adequate to support such an analysis, are not significantly represented by the current state-of-the-art. The state-of-the-art does, however, reveal some examples of methodology and analysis results applied on a micro-scale to specific ports, specific vessel types, and specific channel configurations, which provide some application as baselines from which to proceed.

- The state-of-the-art for radio navigation planning criteria is significantly more advanced than for audio/visual aids. Further, the methods used to define requirements for specific harbor elements are directly applicable to planning for channels working with audio/visual aids, lacking only an equally definitive method of quantitatively defining the operational parameters (accuracy, coverage, reliability).

- Within the objectives of the current Coast Guard study, based on information presently published, sufficient analytical capability for vessel coefficient definition exists in the form needed as an input to the preliminary Process of Navigation model. Insufficient data exists concerning specific coefficients on older, less maneuverable vessels, and very little sea trial data exists for the number of operating conditions which are necessary for simulation.

- Based on discussions and interviews with interested parties, there appears to be a general satisfaction with the audio/visual system as implemented, albeit that implementation has evolved through the application of experienced judgement as opposed to resulting from the imposition of rigid, quantitative planning criteria.

4.2 THE PROCESS OF NAVIGATION

- The process of navigation in restricted waterways is directly related to the information available from navigational aids, and involves incremental navigation, involving a series of guidance and control strategies (tasks).

- Navigation, guidance, and control are conducted simultaneously with visual search, recognition, and monitoring operations.

- There are three general levels of control behavior performed by the mariner in the process of navigation. These levels are precognitive (a learned maneuver executed in an open-loop way); pursuit (relying on preview information upon which the mariner takes advantage of a knowledge of the system inputs in order to structure a control strategy) and compensatory (or regulation, which implies an operation on a perceived error between actual motion and desired motion).

- A singular description of the "process of navigation" is not possible. Although the general process can be characterized, the specific process of navigation must be defined in terms of a specific situation and aid configuration.

- The behavior of the mariner can be appropriately modeled by an estimation function and a decision/control function, specific to the mariner tasks.

4.3 METHODOLOGY FOR NAVIGATION SYSTEM EVALUATION

- No single type of experiment or experimental facility can produce all the results required for the evaluation of aids to navigation. All experimental results, however, can be incorporated into the current model structure.

- The utilization of a computer-based evaluation methodology is essential in order to address, in an organized manner, all of the situations which must ultimately be considered.

- Based on the preliminary model results, the use of fast-time digital simulation techniques can be used for the quantification of the effect of aids to navigation on mariner/vessel performance, and for the quantification of usable and valid vessel safety and traffic facilitation measures.

- Per the discussions of Section 3.6.3, the use of a fast-time digital simulation can be used to reduce the requirements for costly and time consuming man-in-the-loop experiments.

- Validation of the Navigation System Evaluation/Process of Navigation model can be accomplished within the scope of the Phase II effort.

- Based on the Navigation System Evaluation model capabilities and results, and on an analysis of the current procedures for the establishment and disestablishment of aids

to navigation, the SCI (Vt) approach for the evaluation of aids to navigation is considered both feasible and optimum.

4.4 APPLICATION OF THE SYSTEM EVALUATION METHODOLOGY

- While final decisions regarding establishment and disestablishment of aids to navigation involve considerations which cannot be modeled and/or are not to be modeled (such as specific port practices, interest group reactions, budgetary constraints), the overall decision process can be considerably enhanced by the inclusion of objective computer-based results.

- Acceptance of a computer-based navigation system evaluation methodology must stem from a demonstrated correlation between the model results and the "real-world."

- The model is amenable to implementation either on a mainframe or minicomputer system.

- Implementation of the Navigation System Evaluation Model at USCG Headquarters, in the form of an interactive system with computer-aided graphics/display capability (with suitable documentation and training), is the most effective means to provide the USCG with a continuing aids to navigation evaluation capability.

REFERENCES

1. Excerpts from EASAMS Ltd. studies conducted for United Kingdom General Lighthouse Authority.

2. Excerpts from EASAMS Ltd. study: "Study of Systems of Aids to Navigation in the Approaches to the Port of Gravelines."

3. Restricted Waterways Experiment, IIIB Preliminary Data, CAORF, Kings Point, L.I., N.Y.

4. Wagenaar, W.A., P.J. Paymans, G.M.A. Brummer, W.R. Van Wijk, C.C. Glansdorp, "Auxilary Equipment as a Compensation for the Effect of Course Instability on the Performance of Helmsman," Communication Delft, Ship Research Centre/TNO, 1972, 21 p. No. 28S.

5. McLean, J.R. and E.R. Hoffman, "The Effects of Restricted Preview on Driver Steering Control and Performance, "Human Factors, Vol. 15, No. 4, Aug. 1973, pp. 421-430.

6. Wim Veldhuyzen, Dr. ir, "Ship Maneuvering Under Human Control," Chapter IV, Progress Report, Jan. 1973 until July 1976 of the Man-Machine Systems Group, Jan. 1977, printed in Afdeling Der Werktuigbouwkunde, WTHD 95.

7. Kessler, K.M. and A.V. Phatak, "Modeling the Human Pilot During the Tracking Phase of an Air-to-Air Engagement," Final Report prepared for Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, Sept. 1976.

8. Phatak, A.V. and K.M. Kessler, "Modeling the Human Gunner in an Anti-Aircraft Artillery (AAA) Tracking Task, "Human Factors, 1977 19(5), 477-494.

9. Phatak , A.V., N. Gupta, and I. Segall, "Analysis of Controller/System Dynamics for a Remotely Piloted Vehicle Strike Mission," Final Report prepared for Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, Sept. 1974.

10. Krendel, E.S. and McRuer, D.T., "A Servomechanisms Approach to Skill Development, Journal of the Franklin Institute, January 1960, 269(1), 24-42.

11. Sheridan, T. and W. Ferrell, Man-Machine Systems: Information, Control and Decision Models of Human Performance, The MIT Press, Cambridge, Mass., 1974.

12. McRuer, D.T., Allen, R.Weir, D.H., and Klein, R.H. Human Factors, 1977, 19(4), 381-397.

13. Allen, R.W., McRuer, D.T., "The Effect of Adverse Visibility on Driver Steering Performance in an Automobile Simulator," Society of Automotive Engineers, March 1977, Paper #770239.

14. McLean, J.R. and E.R. Hoffman, "The Effects of Restricted Preview on Driver Steering Control and Performance," Human Factors, Vol. 15, No. 4, Aug. 1973, pp. 421-430.

15. Phatak, A.V., "Formulation and Validation of Optimal Control Theoretic Models for the Human Operator, "Systems, Man and Cybernetics Review, Newsletter, Feb. 1977, Vol. 6, No. 1.

16. Wagenaar, W.A., P.J. Paymans, G.M.A. Brummer, W.R. Van Wijk, C.C. Glansdorp, "Auxilary Equipment as a Compensation for the Effect of Course Instability on the Performance of Helmsman," Communication Delft, Ship Research Centre/TNO, 1972, 21 p. No. 28S.

APPENDIX A
STATE OF THE ART REPORT

A.1 INTRODUCTION

This State of the Art report presents information applicable to the requirements of Task IA of the aids to navigation study.

> "Conduct an inventory of information available on the process of navigation and an assessment of the capabilities of persons/facilities to extend that level of knowledge."

In consonance with the specific overall objective of the total project to develop an "analytic technique to design and evaluate systems of aids to navigation," the report will also discuss current system design planning and criteria as a necessary adjunct to the State of the Art. Acquisition of applicable information was pursued by means of the following major efforts:

(1) An extensive interview program with experts in restricted waterway operations was conducted. In most cases, the interviews were based on a structured series of questions intended to reveal actual control processes for vessels under varying conditions of aid to navigation configuration, vessel size, operational objectives, etc. A smaller portion of the interview process involved unstructured discussions intended primarily to cover situations not encountered in the structured questionnaires. The objective was to identify specific operating procedures and techniques used in directing the movement of vessels and the impact thereon of aid to navigation configurations.

(2) Visits were made to authorities, both in the United States and in Europe, responsible for aid to navigation implementation in order to identify existent planning criteria used in establishment/disestablishment, configuration management, and specific system design in response to identified requirements.

(3) Visits were made to representative organizations, both public and private, who are involved in research activity directed toward the vessel navigation problem.

(4) A literature search and analysis was conducted for the purpose of identifying studies or work applicable to the development of aid to navigation system management criteria or which might contribute to the current understanding of the process of utilization thereof.

Details and summarized results are reported herein. SCI (Vt) feels that there is minimum benefit in reporting to the Coast Guard "What they already know". The major thrust of the report therefore is an assessment of the applicability of information and facilities encountered during the above efforts relative to the Coast Guard's desired analytic process. No separate bibliography is presented for this appendix. The source material is identified in the text by name and author.

A.2 EXPERT INTERVIEWS

Interviews were conducted in an effort to help definitize certain concepts regarding the process of navigation and the use of aids. The interview process is probably not the ideal method for acquiring or developing quantitative data regarding decision making and thought processes involved in navigation. However, the information, although both subjective and qualitative, may result in better definition of experimental objectives and/or verification of experimental results. Thus, the following sections are intended to provide not only a report of results but a description of the methods used.

A.2.1 Objectives and Approach

The objective of the interviews was the determination of the state of the art for aid to navigation system installation, planning and utilization thereof by measurable, identifiable

techniques of vessel control, and the identification of the "process of navigation" as understood by the individual conducting it.

Sections 3 and 4 of this state of the art report are directed to the results of system planning, research, and facilities. This section is devoted to methods and results of interviews and discussions regarding system utilization. Since the Coast Guard's primary concern for Phase I of the Performance of Aids to Navigation Study involves deep-draft vessels in coastal ports and harbors, emphasis has been placed on interviewing pilots and masters of ocean-going vessels. However, since coastal ports are populated by a wide variety of vessel types, a limited number of interviews were conducted with tug masters and masters of coastal tankers to obtain their opinions of the aids to navigation used and to identify any differences in their navigation procedures. Finally, casual conversations were held with recreational boatmen in the Annapolis area.

Interviews were concentrated in the Northeast corridor from New York to Norfolk. These areas were selected due to:

(1) The proximity to the Washington area SCI (Vt) office

(2) A diverse combination of aid configurations

(3) Familiarity with the areas by the interviewers

A second group of interviews was conducted in the United Kingdom (individual mariners and applicable organizations) and in Holland (maritime authorities). This set of interviews was selected because of the recent requirement for specific planning for VLCC operation as well as the extensive use of VTS. Neither VLCC's nor VTS are extensively used in the United States, particularly in the Northeast, although certain of the results of European work on traffic control may find direct application in current VTS discussions in New York. Additionally, most European ports retain autonomous authority and responsibility for the establishment of navigation systems, with the central government primarily responsible only for coastal and offshore systems.

Interviews were conducted in several ways. One group in New York was scheduled by appointment for a specific time at a motel conference room. One and one half hours were allocated for each interview and the subjects were paid a consulting fee. Other interviews were scheduled at pilot offices in Norfolk, Baltimore, and Philadelphia. The last group represented interviews "of opportunity"; for example, a tug master was interviewed aboard his vessel which had just completed a run. Structured interviews wherein the questionnaire questions were used as guides were tape recorded. Unstructured interviews and discussions were recorded with notes and chart markups. There is no question that the first method and setting was the most successful and its use is recommended for expansion to other specific port areas during later study procedures. The reasons for this include:

(1) The individuals were preselected by an SCI consultant, himself a highly experienced mariner. They were known to express themselves clearly, or had a particular expertise which was expected to provide valuable insight to a particular element of interest.

(2) The environment was free from distractions.

(3) Because they were in a paid consultant status, the individuals wasted little time on non-related subjects.

It was interesting to note that some of the individuals interviewed had an initial negative reaction to a discussion of aids to navigation. There seemed to be a feeling that an outsider had been engaged by the Coast Guard to develop information which could be used in support of the reduction of the number of existing aids in the name of economy. In all cases, this initial mistrust was overcome and there was no further hesitation on the part of the interview subjects. Many of the interviews could have continued far beyond the scheduled time.

A.2.2 Interview Development

The major objective of the interview process was to elicit information and opinion from qualified experts in the process of navigation as it is applied in the harbor and harbor entrance environment. A second objective was to identify through informal discussions with authorities responsible for implementation of aids, any existing doctrine, planning procedures or criteria directed toward aid to navigation configuration management. The information, although qualitative in nature established an initial basis for the examination of factors impacting on the development of the Process of Navigation model. These factors included specific control techniques, information provided from current configurations, the order of priority in which redundant information bits were used, the degree to which vessel dynamics affected control techniques, etc. The results of the interviews and discussions were applied in the preliminary design of the structure of the process of navigation model as described in Section 3.3.2, which in turn lead directly from the defined elements of navigation discussed in Section 2.2.

Two different interview formats, structured and unstructured, were used. In the structured technique, a group of questions was developed which had a limited choice of answers; for example, the questions were multiple choice or requiring a yes/no answer. With the assistance of a human factors research psychologist, these questions were carefully prepared, reviewed, analyzed, and pre-tested to minimize the time required and maximize the valid information output. In the unstructured format, the subject was asked essentially to discuss all he knew about a subject with periodic questions or comments inserted by the interviewer to maintain the desired pattern. In order to obtain information on the utilization of aids to navigation in the process of navigation, SCI elected to

use an unstructured interview process in the majority of cases, but with the questions and discussions based on the group of structured questions. This approach appeared desirable for the following reasons:

(1) During the proposal development, personnel experience and recommendations from a Sandy Hook pilot (an SCI (Vt) consultant) indicated that the process of navigation was incrementally progressive through harbor modules, i.e. information concerning position and guidance is processed in increments controlled by the characteristics of the harbor module. Specific information regarding this incremental process would lead to a clearer definition of unknowns remaining to be explored in the follow-on phase of the project than would general opinions.

(2) An unstructured interview environment places an individual more at ease and frequently will uncover areas of problems or concern. The structured nature of the questions used by the interviewer permit the discussions to be directed as desired, yielding specifics where available, while at the same time giving the interview subject the opportunity to contribute his own thoughts.

A.2.3 Interview Preparation

In preparation for the interviews, a list of questions was prepared independently by each of a number of members of the SCI (Vt) staff. These lists were then combined into one set, subdivided into specific topic areas. Topic areas included specific harbor element considerations, environmental modifiers (visibility, day/night, etc.) and an area of general aid characteristics and intended usage (lateral vs non-lateral significance, numbering and lighting characteristics, etc.). The question set was then compared with the SCI (Vt) process of navigation model flow diagrams to ensure that all areas would be adequately covered.

The second step involved a thorough familiarization on the part of the interviewers with the geographic areas of interest. Familiarization included reviewing the applicable charts, Coast Pilot and Light List, along with the acquisition

of a general understanding of the traffic types and patterns, prevailing environmental conditions and other applicable operational parameters. This permitted the selection of representative situations (type of ship, channel/areas of operation, tide and current conditions, weather effects, diurnal conditions) for use in the interview.

The third step in the preparation for interview was the pre-test phase, and involved a lengthy and exhaustive interrogation of the SCI (Vt) consultant pilot. The discussion addressed every channel into the New York Harbor through which the pilot operated with a wide variety of imposed vessel characteristics, weather, and visibility conditions. During this pre-test operation, the Human Factors research consultant directed his attention to ensuring that the interviewers were not using leading questions or in any way imposing preconceived ideas or expectation of results.

A.2.4 Interview Technique in Practice

Following an explanation of the overall objective of the study and the intended use of the supporting interview information, the interview subject was asked to describe a vessel transit through a specific entrance and harbor channel enroute to a specific destination. The vessel was to be assumed his own (in the cases of licensed masters) and a selected vessel for the pilots.

The initial transit description was usually quite broad and somewhat vague. To overcome this, the interview subject was interrupted after a few moments and asked specific pointed questions. For example, a sequence such as

"How far from the sea buoy were you when you initiated the turn into the channel?"

"ANSWER"

"All right, then upon what information did you base your rate of turn?"

"ANSWER"

With these types of prompting questions, most interview subjects quickly accepted the need for a complete description of their thought process and they readily adapted. Subsequent descriptions of the transit were made in a more deliberate manner, and involved the necessary operational and thought process narrative desired. Upon completion of one transit, conditions were changed to reflect information desired with the situations becoming increasingly complex in terms of decreased visibility, addition of traffic, etc. When time permitted, the different areas of the port were explored with the pilot or other ports in the case of licensed masters.

During the transit description, the interviewers noted aids which were not mentioned by the subject in the detailed transit description. Follow-up questions were then pursued concerning the non-use or potential value of such aids and the relative value of use of different aids or aid configurations. Finally, the mariner was requested to express his opinion about any aspect of the system which he had considered deficient or superfluous.

A.2.5 Interview Results

A total of 25 interviews of commercial operators, masters, and pilots were conducted, both in the United States and in Europe. An additional 51 interviews "of opportunity" were accomplished by the SCI consultant Sandy Hook pilot, with other such discussions being held with a number of recreational boatmen. Of the more than 100 questions asked in the formal interviews, a lesser number revealed what could be considered definitive information. This is due in part to the design of the question

causing the answer to be either vague or too conditional to be useful. The following is a list of what might best be described as "impressions" resulting from an analysis of the responses. Only those believed meaningful to the current effort have been included.

(1) Aids astern are not generally used. When between "gates," for example, a view of two gates ahead is considered far more valuable than one ahead and one astern.

(2) Leading line ranges are considered extremely valuable. However, opinion was expressed that in a heavily buoyed channel, their use becomes secondary. (Support of CG 222-1-4-6B2-dual ranges should allow reduction of aids?)

(3) The primary method of lateral positioning in a channel is abeam distance. Between aids, the information is based on angles perceived between the vessel's head and the nearest aids ahead.

(4) Maximum rudder used in a controlled (not extreme) situation depends, of course, on vessel size, but 15° seems a reasonably agreed upon desirable limit. The statement was made that VLCC pilots are apprehensive of an unstoppable swing and use no more than 15° if they can avoid it. (Interestingly enough, examination of the sample experiments done at Rotterdam and referred to elsewhere in this report show an almost continuous use of the rudder during a straight passage with extreme rudder swings. The table below illustrates that perhaps preference and actual practice may differ.

Minute	Heading	Rudder Angle
21	118	Midships
22	118	Right 15°
23½	117	Right 30°
24½	116½	Left 45+°
25½	116	Right 20°

(5) In a question involving estimation of distance off centerline, VLCC pilots felt that this could be done to two or three beamwidths, depending on aid spacing, by using difference in relative bearings to buoys ahead, but no clear idea was available on the effect of aid spacing on the accuracy of estimation. Based on European studies, an accuracy of 2-3 beam widths for large ships is obviously unsatisfactory. Note: In this and many other questions, the use of radar was mentioned, even in clear visibility conditions.

(6) With regard to staggered versus gated aids, the frequent use of radar on large ships was mentioned. The opinion was expressed that with staggered aids, there is a tendency to zig-zag, heading toward the nearest buoy.

(7) It was considered that one side marking decreased "perception" accuracy, <u>but not to a significant degree</u>.

(8) Opinion agrees with CG 222 doctrine regarding the desirability of two pairs of buoys ahead. Mariners <u>believe</u> that buoying spacing is proportional to channel width. (The examples of Section 3.1 of this report would seem to contradict this belief.) European respondees mentioned a spacing to width factor of 4 or 5 to 1.

(9) Mariners became concerned about position relative to a bend at a minimum of about 1 ship length from the point where the <u>turn is started</u>, i.e., the helm put over. This distance obviously must be greater than 1 ship length from the bend itself.

(10) It is common practice to use more rudder than necessary to start a turn, easing as necessary to maintain a curved trajectory through the bend. A "kick" in speed is much less frequently used, and only in sharp bends ($>75°$ or so).

(11) Casual opinion (not the result of a structured question) would have it that an error of ½ a ship length can be tolerated in positional error in approaching a bend without emergency maneuvering. One ship length would constitute a true problem.

(12) In negotiating a bend, compass headings are rarely used in control commands. Rudder angles, adjusting as necessary to steady up on the "perceived" heading of the new channel, are used prior to any use of compass heading verification.

(13) American responses tended to favor the opinion supported by Coast Guard doctrine that a mark on the inside of a turning in a bend should be the primary source of information. European opinion differed in a preference for an aid "on your own side" of the channel.

(14) In a head-to-head meeting situation (in a channel), two to three ship lengths (three to four in Europe) seems to constitute the "break point." Channel boundary aid spacing is used in this distance estimation.

(15) An overtaken vessel will generally move to one side in the channel to permit passage of an overtaking vessel.

(16) Most mariners believe that a change in angular aspect of buoys ahead will give more timely information regarding cross track error than will a distance change estimate to the channel boundary.

(17) An entrance buoy, at least one mile in advance of a channel entrance, is considered a requirement for larger vessels. In the absence of such a marking, the vessel will still maneuver to be aligned with the channel heading at least one mile from the entrance when possible.

(18) In only one instance (Sandy Hook) in the United States and Europe did we find an unwillingness to enter a harbor even in zero visibility provided all equipment, particularly radar, was working.

(19) In relatively open water, most large vessels will attempt to maintain a particular track, adjusting as necessary to recover it. Smaller vessels (tugs, coastal tankers) will adjust toward the destination only.

(20) Most mariners felt it would be extremely difficult to proceed from sea to a dock using only fixed aids (although it is done, for example, in ice seasons). On the other hand, they were confident that they could easily do so with only floating aids as presently configured.

(21) Every master and pilot interviewed cited the use of familiar landmarks (church steeple, etc.) as reference points. The one most frequently cited was the "Broadway Range" in New York.

(22) Aid identification is generally by location (familiarization with the area and ship's general position) during the day and by light color at night. Body, color, number, and shape are secondary means.

(23) Most mariners felt that there was a definite requirement for distinctive marking of a junction. None that we spoke to knew the meaning of the term bifurcation.

(24) Unlighted aids are considered anything from a hazard to a nuisance by large ship navigators, particularly in channels where they are installed alternately with lighted aids. They must be designed to be as radar conspicuous as possible.

(25) Long range lights within a harbor complex are rarely used and may have a blinding effect on navigators passing close aboard. Note: This response was recorded referring to New York Harbor. We do not believe the same opinion would pertain in such inland waters as Long Island Sound or Chesapeake Bay.

(26) Audio signals are apparently considered archaic for radar equipped vessels.

(27) With regard to vessel equipment, a number of responses indicated a reluctance to enter a channel in low visibility without radar. There was no significant mention of any other equipment. Some responses indicated a deeper concern with wind and current effects, stating that these effects would be weighed more heavily than visibility in decisions regarding whether to proceed.

(28) Among the pilots interviewed, we could find none that had ever used a pelorus in navigating a harbor.

(29) In a question regarding the relationship of shipboard radar to the number of aids to navigation, European responses indicated an opinion that navigation would be easier with fewer aids, if it was assured that their placement was at key points and they were highly radar conspicuous. United States mariners generally agreed that all the aids were not needed, but would not support the concept of aid reduction with concurrent relocation of those remaining to "key" positions advantageous to radar piloting.

(30) Most mariners interviewed stated that visibility began to affect their decision-making process when it fell to about 2 miles. 3½ miles or so is considered generally "good" visibility. Visibility of 10 miles or greater is considered, operationally, a meaningless measure.

(31) As previously noted, radar is almost continuously used even in clear visibility when maneuvering through a harbor.

(32) United States mariners indicated that they would welcome any radio navigation technique that would help them identify position, velocity, etc., but they expressed concern regarding the reliability of such systems and definitely would not accept such a system as valid rationale for replacement of visual aids. (The Coast Guard has already encountered this type of reaction in some areas (San Francisco Harbor), and the reaction epitomizes the need for educational efforts.)

(33) Mariners agreed that one-way channels frequently simplify passage through that channel but, surprisingly enough, felt that such a technique could conceivably cause more problems than it cures. Mariners felt that a point of confusion exists where the traffic again becomes two-way and intermixed.

(34) The most critical channel/harbor element is the bend, regardless of its configuration (junction, turning point, channel entrance).

(35) Mariners felt that an overabundance of aids can definitely lead to confusion and misidentification, particularly at night. Synchronization of aid lights was mentioned as one method of alleviating identification problems.

(36) Responses from Europe indicated the opinion that the greatest potential for stranding lay in misidentification of aids. In the United States, the majority of opinion assigned this risk to misjudgment of winds and currents, an opinion which seems to be borne out by accident data.

A.2.6 General Conclusions

The interview results, as summarized in the preceding section, provided no "surprises" in terms of utilization of aids, or the processes of navigation. The interview effort was directed primarily to navigators of large ships and the results can be considered predictable, at least in the opinion of those members of the SCI (Vt) staff who had experience in vessel navigation. If any impressions could be said to stand out in the analysis of the answers, they would involve the following:

(1) The continuous use of radar, even in good visibility, seems universal.

(2) The willingness to proceed under the most restrictive visibility conditions is interesting, with current and wind conditions being considered more important limitations than visibility.

(3) The opinions regarding the lack of need for longer range fixed lights, in favor of shorter range but more

informative floating aids (providing guidance as opposed to position reference).

Although not specifically researched, we believe that an examination of the history of the implementation of the aid configurations would reveal that the lighthouses were first installed when certain of the harbor areas were capable of treatment as "open water," i.e., in the era of smaller, shallower draft ships. The buoyage system then grew as the criticality of channel project depths grew, in effect obviating the need for many of the longer range lights in a harbor environment. As previously indicated, such areas as Long Island Sound or Chesapeake Bay, where formalized plotting procedures may on occasion be used, still require a certain number of longer range position references.

(4) The fact that 3½ miles was considered "good" visibility and visibility began to affect the process of navigation at 2 miles. This point seems verified in a paper examining the problem of groundings ("Stranding of British Merchant Ships" Nautical Review, July/August 1977) wherein "thick weather" is identified as 2 mile visibility or less. These opinions seem to indicate the desirability of examining (perhaps through experimentation) the placing of long distance lights vis-a-vis shorter range configurations for visual aids.

(5) The use of unlighted buoys in <u>major</u> channels seems to be in question.

The potential benefit of the qualitative and subjective interview results seem to be mainly in the revelation of areas in the process of navigation which seem to require experimentation in order to arrive at quantitative verification of some of the opinions expressed. A simple relationship such as the ratio of channel width to aid spacing has, as yet, not yielded to definitive criteria.

A.3 SYSTEM PLANNING CRITERIA

A.3.1 Planning for Visual Aids

The State of the Art Survey had as one basic objective the identification of codified, quantitative planning criteria for aids to navigation which include the application of process of navigation parameters. None of significance could be found in the Audio/Visual category. Significant amounts of data are available on aid characteristics such as range of visibility, recognition data, size, shape, message, and, to a lesser extent, information content. However, with regard to configuration vis-a-vis a particular waterway arrangement, the answers invariably reduced to the application of "experienced judgment." This is not necessarily an unsatisfactory approach as long as the "experience" is available and the "judgment" accepted. Interviews revealed a general satisfaction with the aid configurations and with the established lines of dialogue between interested mariners and the local Coast Guard authorities. One of the problems is obviously the fact the local configurations evolved over many years by the addition or relocation of aids, rarely by disestablishment. It would be an exceptional situation where disestablishment of an existing aid would be requested of the Coast Guard by the local mariners or that unilateral disestablishment would not result in adverse reaction.

The evolution of aid configurations in one district has reached the point that, according to the district A to N officer, 85-90% of all new aids are established to meet requests/requirements of recreational boaters. In that same district, the local

U. S. Navy organization has successfully supported an aid configuration which might seem overdesigned when compared with the marking for similar waterways elsewhere. Justification for the arrangement is based on the fact that the largest aircraft carriers and other large Navy vessels are major users of this channel and the characteristics of these vessels require the aid configuration. This may very well be true. No quantitative data, however, is available here, or elsewhere, to support the contention (or dispute it). This is one of the objectives of the current study.

Obviously, the responsibility of the Coast Guard covers large areas, with many special, localized, unique problems. Each port has its own peculiar problems, which defy analysis other than by experienced judgment. There are, however, certain common harbor elements throughout the areas of Coast Guard responsibility and these may very well lend themselves to configuration "standardization" based on an analytic definition of the navigation process. The Coast Guard is more definitive than any other authority examined with regard, for example, to buoy placement criteria. Section 4-5 of the Aids to Navigation Manual (222-1) provides the following quantitative criteria:

(1) In marked channels, an operator with a five foot or greater height of eye need see no more than two aids ahead of him on each side of the channel.

(2) Average spacing on the same side of channels requiring marking should be:

Exposed Environment – 1 mile
Semi-Exposed Environment – 3/4 mile
Sheltered Environment – ½ mile

For the most part, however, criteria appearing in the doctrine, while significantly more comprehensive than those published by other responsible authorities, are qualitative in nature. In only one instance, for example, (Daybeacons – Para. 4-6D) is

policy stated with regard to a choice between "gated" and "staggered" configurations.

SCI (Vt) believes there is no means by which "experienced judgment" can be eliminated from the planning process. Likewise, a significant amount of the aid to navigation inventory will be totally unaffected by a quantification of the process of navigation. Qualitative, subjective criteria must apply. However, there is also a significant amount of navigable waterway which is common throughout the system regarding the requirements for marking and to which general conclusions with regard to the process of navigation may be applied. These harbor elements include channels, i.e., areas of safe water, bounded usually on both sides by shallow water. Channels bend, widen, narrow and cross (junctions). Channels have a defined width, a minimum depth, and a finite length. These are quantitative parameters. The markings used to define the channels can be configured in a relatively small set of alternative arrangements, each of which has specific design characteristics. For example, buoys intended to define channel boundaries can be configured as gates, staggered pairs, or single side markers. Channel centerlines can be marked with leading line ranges or fairway buoys. Given a decision on the particular configuration, the remaining decisions involve only aid spacing and detectability (lighted, unlighted, radar reflector equipped).

To summarize, the following functional relationships appear to exist:

Aid Characteristics		Operational Requirements
Configuration Spacing Detectability	as a function of	Channel Width Channel Length Susceptibility to Cross Channel Effects Vessel Maneuverability

As discussed in Section 3.5, the development of valid design criteria depends on the success with which the Coast Guard study

identifies and quantifies these functional relationships. The decision-making process involves some definition of the effectiveness of the aid characteristics. This, the unknown in the current state of the art throughout the world, is the subjective input to the equation. The results of this subjective input (and evolution) can be illustrated with a few specific examples.

A.3.1.1 New York Harbor

(1) Ambrose Channel – Length, approximately 8 miles; width, 2000 feet. Two shallow bends (30% or less). Marking: Gated Pairs.

Outer Leg (4 Miles) – Lighted buoys spaced approximately 2000 yards. Unlighted buoy gates approximately centered between lighted gates.

In daylight, therefore, this leg is marked by gates with approximately 1000 yard spacing. At night, the marking is gates with 2000 yard spacing (ignoring the use of radar).

Center Leg (1 Mile) – Marked with lighted gates spaced at approximately 1000 yards.

Inner Leg (1.3 Miles) – Marked with lighted gates spaced at approximately 1500 yards.

One can examine the spacing and postulate an associated rationale. Since there obviously is advantage in the process of navigation to symmetrical buoy spacing, the lengths of the marked legs can be correlated with the designed spacing. The use of unlighted buoys on the outer leg reduces the spacing to 1000 yards (for the radar equipped ship) and a different day/night spacing for the non-radar equipped ship. Questions naturally arise regarding the need for the unlighted buoys. If a ship is not radar-equipped and uses the channel at night, the spacing must be considered 2000 yards. If this is satisfactory for the non-radar ship, then it must be considered satisfactory for the radar ship, and hence, why the unlighted buoys?

(2) Raritan Reach (East and West) – Length, approximately 7 miles; width, 600 feet - Straight Channel.

Marking – North side of channel: alternate lighted and unlighted buoys spaced at approximately 1300 yards. 2600 yards between lighted buoys.

Marking – South side of channel: three lighted buoys (in first $5\frac{1}{2}$ miles) forming a gated pair with every other lighted buoy on the north side. (Spacing – 5000 yards).

A number of points should be noted here. This channel is less than half as wide as Ambrose Channel, yet the buoy spacing on the north side is greater than in Ambrose. On the south side, the buoy spacing is almost $2\frac{1}{2}$ miles or 5 times that of Ambrose. A question naturally arises regarding the difference. Why is the narrower channel marked with fewer aids in what must be considered a configuration with a lower level of information content?

The comparison of these two channels in the same harbor is not intended to point out deficiencies in the system. Discussions with the New York pilots indicated satisfaction with the aids as configured, and there is certainly no definitive data on hand which could support any modification or define what form that modification might take. This is the way it is, this is the way it has been, and it works. Why change it and on what basis? The examples are intended to point out apparent anachronisms in configurations which evolved by increments and to illustrate design and operational parameters which may lend themselves to a quantitative approach.

The point does not require belaboring, but one additional comparative example might serve to validate the contention.

A.3.1.2 Chesapeake Bay

(1) Thimble Shoal Channel – Length, approximately $9\frac{1}{2}$ miles; width, 1000 feet - Straight Channel.

Marking – Lighted gated pairs spaced at 2000 yards.

(2) York River Entrance Channel – Length, 10 miles; width, 750 feet - Straight Channel.

Marking – Alternate lighted and unlighted gates, spaced at approximately 2500 yards (5000 yards between lighted gates).

Again, we see two straight channels, the narrower of which is marked with a system of significantly lower information content than that of the wider. (2½ to 1 in the case of lighted gates.) However, as in New York, discussions with local mariners revealed no dissatisfaction. The system works and any effort to significantly modify it would probably result in adverse reaction, unless such an effort was based on acceptable analytic data.

A.3.1.3 Conclusion

In examining the "state of the art" in audio/visual aid system planning, our first conclusion is that, of the authorities visited or described in the literature, the Coast Guard has the most definitive set of planning and design criteria. During European visits, discussions with the authorities there revealed that "experienced judgment" is the basic input to the planning process, as it, of course, should be, and little attention is paid to any analytic approach to the navigation process. There is a significant amount of discussion and at least one example of experimentation regarding buoy design and the use of cardinal versus lateral ranking (see "An Experimental Buoyage System" by Captain J. E. Bury), but significant efforts toward configuration management do not appear.

The second conclusion resulting from this survey is that the Coast Guard appears faced with a formidable task in applying quantitative planning criteria to an aid to navigation system which has evolved over a period of many years. As far as can be determined from discussions and interviews, the customer is essentially satisfied.

A.3.2 Radio Aids to Navigation

Probably because they are relatively new on the scene and readily available to technical evaluation, radio aids to navigation appear to have been implemented under a more stringent set of planning criteria than are available for audio/visual aids. The accuracy of a radio navigation system is a measurable parameter. The "accuracy" of a buoy remains to be defined. Subject only to economic limits, radio navigation techniques can cause track lines to be drawn on charts or can present information in just about any desired form; e.g., position in any desired reference frame, relative and true velocity, position error relative to an established radio reference, recommended courses of action — the list is practically endless. Theoretically, technology is capable of completely bypassing the human operator. Extensive planning studies for large area coverage radio systems or for micro-area special operations are available.

No purpose is served in reciting a list of the studies which resulted or will result in the definition of requirements and the system technology implemented in response thereto. The Governments of Norway in 1960 (CONSOL, DECCA) and the United States in 1974 (OMEGA, LORAN-C) mounted such efforts. Of significantly greater application to the objectives of the current Coast Guard study effort are the analyses of requirements and resultant system definitions for the ports of Antifer and Gravelines (cited elsewhere in this report). These studies are representative of the highest level of the current state of the art in planning for navigation aids in harbor modules using analytic techniques. If the information available from an audio/visual system can be defined, with appropriate statistical limits, to a degree similar to that of radio aids, the methods of analysis become immediately applicable.

A.4 FACILITIES

A.4.1 Objective of the Facilities Survey

The statement of work for this project requires a summary of personnel and experimental facilities representative of the state of the art in investigations of the process of navigation including an assessment of their potential for further investigation and research. Such an assessment involves three elements:

(1) An understanding of the direction, method, and facilities (including personnel) of current investigative efforts.

(2) An examination of facilities not currently engaged or used in research efforts, but which conceivably could be so applied.

(3) A clear definition of specific Coast Guard objectives in Aids to Navigation system studies. The assessments must be based on the specific outputs desired from the efforts and the decision areas which presumably will be based on those outputs.

A.4.2 Facilities Surveyed (General)

Systems Control, Inc. (Vt) considers that the ultimate results of the current study are establishment/disestablishment criteria for audio, visual, and radio navigation systems used in general navigation operations. Examination of current efforts reveals a number of sophisticated studies and research projects directed in each instance toward a particular and unique set of circumstances and resulting, in most cases, in the development of highly specialized techniques largely based on radio aids. Examples of such efforts can be found in the studies done for the Europort (Hook of Holland, entrance to the new waterway and VLCC terminal at Rotterdam), Gravelines (Dunkirk), Antifer (Le Havre), and recently such specialized efforts in the United States as the mini Loran-C chain in the Great Lakes and the latest current investigations into aids

to navigation in the harbor of Valdez. None of these efforts, although representative of the state of the art of navigation system planning, in our opinion, represents the process or addresses the questions regarding deployment of elements of the general purpose aids to navigation system, throughout the total areas of responsibility of the Coast Guard. Each of these special cases can be considered micro environments which lends itself to micro analysis. The problems are well defined and have the tremendous advantage of allowing a "start from scratch" approach. The results invariably support the installation of sophisticated systems and equipment.

Our research indicates that there are no present or past investigatory programs (with the possible exception of some recent experiments at MARAD's CAORF research facility) which seem generally applicable to the development of Establishment/Disestablishment criteria for the general aid configurations composed of buoys, lights, etc., which constitute the overwhelming majority of aids both in numbers and cost serving a navigation community of wide diversity. The current system has grown and been deployed largely without the benefit of generally applicable and codified standards other than the application of judgment and experience existing in Coast Guard and maritime individuals and organizations. Operationally, this is not necessarily disadvantageous. The audio/visual system seems adequate, and nowhere did interviews with experts in the field surface any significant dissatisfaction with the system. Economically, however, there seems the potential of significant benefit in a reappraisal and modification of the process. After a review of current and past efforts, SCI (Vt) believes that the most advanced approach to the problem of overall systems planning for aids to navigation is that being pursued by the Coast Guard in the present study. Hence, the assessment of facilities which follows is an assessment of the applicability to the present project based on demonstrated capability in more specialized areas. The question to be answered is simply, "How can these specialized capabilities

be expanded and/or redirected to yield results generally applicable to the planning for an overall integrated system of aids to navigation?"

The SCI (Vt) approach to the current project is the development of a "process of navigation" model within a Navigation System Evaluation Model. The validity of the results of this approach depends significantly on quantification and algorithm development for various elements of the system, techniques of use, and equipment available. Our assessment of facility capabilities therefore is directed toward the potential usefulness of the facility in determining or verifying the validity of the inputs to the Process of Navigation model and the information content of the aid to navigation system under evaluation. It is SCI's contention in this report that the benefit of an examination of facilities representing the "state of the art" in maritime research does not lie solely in a simple listing of those various facilities, equipment, personnel available, and direction of efforts currently underway, but in a specific appraisal of how the current "state of the art" can, in general, be utilized to answer the questions posed. For example, the number of facilities which use sophisticated radar simulation systems is large. No benefit accrues from a listing of all those so engaged. The benefit lies in an examination of how a sophisticated radar simulator can be applied to investigations of the type required for this project. Similarly, large scale ship simulators are available in a number of locations. While there are probably greater differences in capability among these installations than is the case with radar simulators, nevertheless, the final assessment lies in the <u>definition of the questions to be answered</u>, followed only then by an evaluation of the applicability of a large scale ship simulator to obtaining the answers thereof.

The type of facility applicable to the problem will fall in one or more of three general categories:

(1) Personnel Training Facilities

(2) Research Facilities

(3) Operational Facilities

In each case, the discussion will involve the potential applicability of the facilities and equipment generally available. Specific facilities will be addressed only when the capability possessed is unique. Examples of special techniques will be cited where deemed appropriate.

A.4.3 Personnel Training Facilities

In general, personnel training facilities have at their disposal two assets applicable to the program viz:

(1) Knowledgeable Personnel

(2) Simulation Capability

The simulation capability may range from the most basic simulation of radio navigation equipment or radar presentation combined with minimum "own ship functions," to highly sophisticated ship simulation which includes all aspects of audio and visual effects, radar operation, vessel dynamics, communications, and choice of geographic area of operation.

At the present time, such facilities are dedicated to one or more of three objectives, depending upon design and sophistication:

(1) Training in shiphandling/maneuvering as a function of vessel size and operating characteristics

(2) Collision avoidance training based on radar and/or visual information

(3) Navigation and piloting training for particular classes of vessels based on simulation (radar and/or visual) of a particular geographic area

A.4.3.1 Training Simulators

Training simulators are usually found in one of two forms, although there may be common capability in each.

(1) Radar Simulators: Radar simulation is directed exclusively to the training of shipboard personnel in collision threat assessment and avoidance, and in the techniques of radar piloting.

The typical collision avoidance equipment will include one or more own ship units, which control the simulated radar equipped vessel and include desired vessel dynamics and tactical characteristics. Each such own ship unit is associated with a radar display. In the usual case, displays are standard marine equipment interfaced with the simulation computer and may be simple (head-up, unstabilized) or as sophisticated (stabilized, doubly stabilized, true motion) as required by the training activity. A number of "slave" displays may be included, such displays simply acting as repeaters for the own ship controlled "master" displays. The trainee, or experimenter, may evaluate the presentation on a "slave" display in the same manner as is done on a "master" without, however, the capability to perform maneuvers. A digital computer (typically, although some analog types are still in use) generates video input to the displays in the form of target ships and controls the position of all own ships relative to targets in accordance with courses, speeds and initial relative positioning. Some simulators permit pre-programmed exercises with changes in target ship courses and speeds occurring as the problem develops. Typical auxiliary equipment includes X-Y plotters for post-problem analysis, ship-to-ship communications, and simulated radio navigation information. External effects such as yaw, current, noise, sea return and ship shadow areas are available.

(2) Radar navigation capability is provided via so-called "coast-line" generators. Land contours with or without radar shadow effects are generated and displayed along with the actual configuration of aids to navigation. A flying spot scan of a "negative" is normally used for image generation although some modern installations use a digitally programmed image.

General Assessment

Radar simulation installations contain a significant potential for experimentation in aid to navigation configurations. Interview information indicates an almost continuous use of radar by pilots, even in clear visibility. Most installations provide the option of radio navigation integration (Decca, Loran-C, Omega, RDF). One significant advantage of the radar simulators used at training facilities over ship simulators (which may include a radar simulation in conjunction with the visual) is the availability of multiple operating stations permitting simultaneous "perception" type experiments with as many subjects providing data on the identical configuration as there are displays. For radar investigations of aid to navigation configurations, the "coast-line generator" equipment provides a simple way to vary aid configurations. At least one training establishment (London Polytechnic) had developed an "in house" capability of developing displays with the intent of using them in a variety of experiments. An additional technique available is the use of stationary "target" ships in an open sea presentation as aids to navigation with no manipulation of the coastline generator being required. Hence, if one desired to test aid spacing or configuration in a navigation environment, he need only position the stationary target ships as required and observe the radar navigation process through this "aid" configuration.

Radar piloting techniques are used in large numbers of operating situations and an evaluation of aid configurations must consider them. Radar training simulators are considered applicable and recommended for definition and refinement of data input to the process of navigation model in the following areas:

(1) Verification of scale preference versus aid configuration, choice of display type, and use of controls

(2) Type and accuracy of measurements accomplished using display equipment (cursors, heading flash, etc.)

(3) Actual radar navigation process versus aid configuration

(4) Method of determination of and reaction to such effects as leeway, sea return, radar noise and shadow effects

(5) Collision avoidance techniques and threat assessments in channels

(6) Degree of use of geographic topographic features in conjunction with or in lieu of installed aids

(7) Application of ship tactical characteristics when maneuvering in a particular combination of harbor elements

(8) Use of maneuvering "cues" such as ranges of opportunity, aids abeam, etc.

Advantages

(Note: The following are inten ' to compare the use of existing radar simulators with existing ship simulators in those areas of applicability common to both.)

(1) Multiple operating stations allowing simultaneous experiments

(2) Ease in aid reconfiguration

(3) Simplicity of performing experiments using basic aid configurations (by positioning of stationary target ships)

(4) Relatively low cost.

Disadvantages

(5) The effect of vessel size and dynamics, while built into the control function provides minimum "feel" for the ship.

(6) The usual design of own ship control bears little relationship to the organization of a ship's bridge.

A.4.3.2 Ship Simulators

As used herein, the term "ship simulator" is intended to refer to any simulation which involves a combination of ship control within an environment which includes audio/visual presentations

viewed from a mock-up representation of a ship's bridge. Inputs from other navigation sensors such as radar, radio navigation, and communications may be available. The ship control function includes vessel characteristics and is usually performed on standard marine type equipment such as to reproduce the actual appearance and organization of a ship's wheelhouse. Such simulators have only recently become available with the sophistication necessary to provide a full range of operational training. The state of the art has been significantly influenced by similar simulation installations for airplane pilot training where it has been found possible to perform qualification checkouts in lieu of actual flight demonstrations of proficiency. Historically, the use of ship simulation was directed toward the training of naval personnel in shiphandling, maneuvering, and control of vessels in tactical situations. The World War II ASW "Attack Teacher" is an example of such a design. With the advent of larger, potentially more dangerous merchant ships, and the expense of "on the job" training, a recognition of the necessity for more sophisticated simulation developed. The first major effort involved the actual scale modeling of vessels with the operator physically located inside the model (Grenoble, France); the objective being the training in shiphandling of large vessels combined with a visual aspect of the vessel itself as viewed from the control station. The ultimate capability at the present time in the United States is that represented by two ship simulator installations, each of which provides a full scale ship's bridge provided with standard operating equipment, with a full scale visual presentation of the vessel and its surrounding environment. The basic difference between the two is in the generation of the visuals. Each use television projection for presentation, but in one installation MARAD's Computer Aided Operational Research Facility (CAORF), the image is generated in a digital computer which then drives the video projection units. The other large scale simulator is operated by Marine Safety International (La Guardia Airport) as a training aid for use in conjunction with

training programs presented to ship's crews on behalf of client maritime companies. The MSI installation uses scale models of geographic areas constructed on model boards through which a small television camera probe is magnetically guided in accordance with control signals from the ship's bridge processed through a digital computer. From the point of view of the applicability of these installations to aid to navigation experimentation, certain differences between the two designs are significant.

(1) The CAORF system is more versatile in the range of visual presentations possible; in particular, the inclusion of other ships in the area of the operating ship and the maneuverability thereof. At the present time, other ships on the MSI installation are scale models magnetically controlled along tracks beneath the model board.

(2) There is some disagreement among researchers as to the relative quality of the visuals developed by the alternate systems. It is our opinion that for small, multiple configurations of buoys, etc., the scale model perceived by the television probe (MSI) may provide some advantages in perception to the digitally generated aids of CAORF. However, an improved optics system is scheduled to be installed in CAORF, which will improve resolution, although computer quantization limitations will still be present.

(3) The CAORF presentation does not provide parallax effects; hence, the view from one wing of the bridge is the same as that from the other.

(4) The integration of the radar information with the visual at MSI is accomplished via a standard coastline generator with the "negative" from which the picture is being developed independent of the model board, thus requiring calibration and the possibility of relative error.

(5) MSI is, at the moment, strictly a training installation and does not necessarily seek work in research programs. They are fully scheduled (during working hours) through calendar 1978 for training programs. CAORF is currently more available for extended and specialized research experiments.

(6) The MSI concept of the televised model board lends itself to much simpler, more rapid, and consequently less expensive reorientation of a configuration of visual aids within an operating region.

(7) The MSI facility has limited data recording capabilities (no mechanism to record rudder action, cross track, etc., versus time). A mini-computer only has coded vessel dynamics and a minimal amount of scoring programs to aid in operator training.

(8) Angular distortion exists in the MSI optical display system. At approximately 30 percent off centerline, the discrepancy can be as much as 5 percent.

A.4.3.3 General Assessment

Either of the two large scale ship simulators discussed above has significant potential for the acquisition and verification of a variety of the process of navigation parameters used in the model under development by SCI (Vt). One of the advantages of the SCI (Vt) approach is the fact that once the significant parameter is defined via the use of large scale simulation, the navigation problems may then be run using high speed simulation, any desired number of times, varying the parameters within the verified limits without the necessity of returning to the time consuming exercises of the ship simulators. The ship simulator's greatest value in this program, therefore, would seem to be an original series of experiments to establish parametric limits and, perhaps, a final series to verify results, with analysis of the variations of the problem being performed via the high speed model developed under this contract by SCI (Vt).

A.4.4 Dedicated Research Facilities

A number of organizations and institutions are dedicated in whole or part to Maritime Research. These include government facilities, academic institutions and private concerns. In visiting a representative sample of such organizations and reviewing the literature, it seems clear to SCI (Vt) that current efforts are primarily directed toward either:

(1) Collision Avoidance/Traffic Control

(2) Special Case navigation problems usually involving superships and narrow, environmentally encumbered channels. Additionally, a significant amount of work has been accomplished on single aid hardware (daytime and nighttime visibility, radar cross section, etc.) and radio aid systems. Significant improvements have been made in the field of optics. However, these improvements have rarely resulted in changes in installed aid configurations. The aids themselves have been improved and made more effective, but no significant rearrangements or (particularly) disestablishment actions seem to have resulted.

Nowhere can we find any significant work directed toward the general problem of standardization of criteria for large scale implementation of integrated aid systems, nor definitions of effectiveness measurements thereof. The information from responsible authorities in the United States and Europe is overwhelming in favor of "experienced judgment" as discussed previously. Only recently have significant efforts been mounted on the measurement of applicable human factors such as those underway at the Maritime Research Center at Kings Point, New York.

A.4.4.1 Computer Aided Operations Research Facility (CAORF)

There seems to be no question but what the greatest immediate potential for experimentation in the general process of navigation lies in the use of large scale ship simulation. The only such simulator dedicated to research in the United States is the Maritime Administration's Computer Aided Operations Research Facility (CAORF) at King's Point, New York. The general capability of this installation was discussed in the previous section. The value of CAORF lies in the capability to conduct real time experimentation in the decision-making process and the acquisition of quantifiable definitions of the quality of "perception" of the human in arriving at such decisions.

In general, experiments necessary to verify the inputs to the process of navigation involve the measurement of information

desired from a particular aid or configuration of aids. SCI (Vt), in developing its process of navigation model, has identified a number of parameters in the form of distances and angles which are available as quantifiable information. Harbor modules have been identified which can be marked in alternative ways. In order to properly process the information, the choice, accuracy and sensitivity of the parameter and its measurement or "perception" must be known within assignable limits. Large scale ship simulation permits the observation of the navigation process under controlled conditions by recording the maneuvers accomplished and, at the same time, noting the use of available information contributing to the control decision. The decision-making process, the quality of information upon which decisions are based, and the success of the decision in a defined environment is the heart of the "process of navigation."

A "real world" approach to this was performed and reported in the Coast Guard sponsored study "Pilotage in Confined Waterways/ The United States — A Preliminary Study of Pilot Decision Making" (Huffner). A discussion of this technique is contained in Section A.5.5 of this report. More recently, the Coast Guard has been pursuing experiments on the CAORF simulator facility (The Restricted Waterway Experiments). Such experiments, if confined to identified aid configurations and harbor modules, do not require an inordinate amount of time per experiment. SCI (Vt) intends to list and define such further experimentation considered necessary for validation of process of navigation parameters in its proposal for Phase II work. The results of Phase I will demonstrate the feasibility of the model as developed. Large scale simulation can be used to verify the quantification of the parametric inputs necessarily estimated during the Phase I effort.

A.4.4.2 Private Research Organizations

Private organizations which devote a majority of their effort to the marine aid to navigation problems are, for all practical purposes, non-existent in the United States. While there are a number of highly competent companies capable of the pursuit of studies in all aspects of the problem, there seems to be none that specialize therein. In the United Kingdom, however, EASAMS Ltd has an impressive background in the performance of aid to navigational analytic studies for a variety of authorities, and in a wide spectrum of applications. EASAMS was visited by SCI (Vt) representatives during November 1977 at the suggestion of the Coast Guard and copies of documents representative of their work were obtained. The information booklet provided by the company (Capability in the Specification of Marine Aids to Navigation) presents a picture of significant capability and depth of experience. Examination of certain of the studies cited in the publication revealed methods of analysis of both general and specific navigational areas which can be considered applicable to the current Coast Guard effort. The following brief descriptions illustrate the approaches taken:

(1) Coastal Navigation Systems Study for the General Lighthouse Authorities (August 1977)

This study proposes the application of methods to assess aid to navigation system "effectiveness." "Adequacy" of the system is then defined as the minimum level of effectiveness which will reduce the navigator's positional uncertainty to within acceptable limits. The interesting element of the approach is the reduction of definitions of effectiveness and adequacy to probabilistic terms with the primary criterion for adequacy being "accuracy." Basic rules of thumb are proposed for accuracy requirements in two operating situations representing the areas under study, specifically "Within a Traffic Routing Scheme" and "Elsewhere" (other than port approaches).

The EASAMS GLA study is concerned with Coastal aids to navigation and the results therefore are not directly

applicable to the current Coast Guard study. The methods seem appropriate, however (in fact, the effectiveness versus adequacy measure corresponds essentially to the approach proposed by SCI (Vt) in the current study viz. Required versus Achievable accuracy). The General Lighthouse Study, by EASAMS, represents a "state of the art" effort in aid to navigation evaluation and exemplifies a capability on the part of that organization to contribute to follow-on Coast Guard study efforts.

(2) Study of Systems of Aids to Navigation in the Approaches to the Port of Gravelines

(3) Definition Des Aides Radio Electrique Aux Approaches D'Antifer

These two studies by EASAMS are jointly cited as epitomizing certain highly sophisticated approaches to the definition of aid to navigation requirements for highly specialized ships (VLCC's) in a particular port. The studies not only define positional accuracies required in terms of along and across track error but also accuracies required in the measurement of along and cross track velocities. Additional analyses included address the problem of ship dynamics, "effective" ship width, and the assignment of an on-board reference point to which the position and velocity information is referred. Interestingly enough, analysis of the factors involved indicated that the vessel's "pivot" point as the maneuvering reference was unsatisfactory with large vessels in shallow water of varying depth, thus seemingly contradicting generally accepted procedures.

The Antifer and Gravelines studies typify an approach to the specialized harbor/vessel problem. In the U.S., for example, the port of Valdez, the Houston ship channel, or certain areas of the Great Lakes present similar problems. The results are minimally applicable to the general problem addressed in the current study, but the methodology probably represents examples of the most sophisticated theoretical approaches which can be applied.

A.4.4.3 Academic Research Organizations

In the United States, university research in the areas impacting directly on marine aid to navigation design and evaluation is

not widespread. A significant effort is mounted in related fields, such as Oceanography, but associated navigation studies invariably deal with specialized positioning devices and techniques. Extensive work is accomplished in Naval Architecture and hydrodynamics, but little is done in relating such work to the aid to navigation problem. There is no question regarding availability of intellectual talent and other research resources. The problem seems simply that, with a few notable exceptions, the requirement for such research has not been established with sufficient priority. This may be the result of the federal government's role in maritime research. Both the Coast Guard and the Maritime Administration have mounted aggressive efforts in all aspects of maritime research, but the majority has been oriented towards either vessel economics or regulatory control, and the work has been primarily in-house or contracted to commercial facilities.

A small amount of maritime research has been accomplished through academic organizations. For the maritime institutions, the thrust has again been either economic or vessel characteristics, which may be interrelated. The Coast Guard has sponsored R&D at several institutions where C.G. students are accomplishing graduate work in optics/physics. This work has been engineering-hardware oriented, i.e., better batteries, optics, etc.

Many of the educators at the five state and two federal maritime oriented institutions have engaged in research activities. The forum for many of their programs has been the Institute of Navigation. A review of the papers presented at the ION symposiums reveals a trend towards offshore navigation systems such as Loran, Omega, and Satellites or collision avoidance. Only a few papers have been presented on shore aids, and again, these are hardware oriented. This is quite understandable in that the institutions have hardware available for training and personal research of the instructors.

A significant amount of research activity in maritime areas is accomplished at academic institutions in Europe. At the suggestion of the Coast Guard, representatives of SCI and the Coast Guard jointly visited the City of London Polytechnic's Marine Traffic Research Unit. The objective of the visit was to investigate the directions and methods of research being conducted. Discussions were held with Dr. Elizabeth Goodwin, a widely published researcher in marine traffic studies. The Polytechnic has a radar simulator installed with "Standard" capabilities as described in Section 4.3. The work of the unit is directed primarily toward the areas of traffic analysis and collision avoidance. Of the projects underway, only that of J. L. Strange (Experiment on the use of information in the making of navigational decisions) seemed directed toward the general problem of aids to navigation. The experiment, in its present form, is intended to assess preferences for and confidence in the various forms of navigational information available. The Polytechnic carries out both training and research in maritime disciplines using the installed simulator in each.

The following academic institutions also mount a significant maritime research effort in conjunction with training and education. They were not visited due to time limitations but their reported areas of research are listed below:

(1) Liverpool Polytechnic, Department of Maritime Studies

(a) Navigation Studies
(b) Passage Planning
(c) Human Factors
(d) Incidents/Casualties
(e) Navigational Practice
(f) Navigational Error Analysis
(g) Radar and Collision Avoidance Training

(2) University of Wales Institute of Science and Technology

(a) TV picture generation for simulation

(b) Automatic Guidance

(c) Computerized Radar

(d) Ship Simulation

(e) Application of control engineering to navigation

Even a cursory examination of university-based maritime research in such other nations as Norway, Sweden, Holland, Japan and many others leads to the conclusion that the level of such effort abroad is significantly greater than in the United States, while the number of private organizations performing maritime research under federal and industry sponsorship in the U.S. is relatively larger than the same approach abroad. The reasons for this may lie in the centralized U.S. federal responsibility for maritime matters as well as the relatively low position of maritime research in the totality of areas demanding attention. There is no question that major maritime nations will support maritime research.

Summary

There is a potential untapped research source in U.S. academic institutions, particularly those which are maritime oriented. Although most of these institutions only have undergraduate programs, many have special scholar programs during the senior year which could be exploited. To accomplish academic research, major programs should be subdivided so that students can accomplish objectives within the allotted time frame.

In addition to student research, academic interest could be promoted through the wealth of operational experience available in the instructors, and their access to equipment such as radar simulators.

A.4.5 Operational Facilities

There is precedent for the use of operational facilities in the acquisition of data such as that required for the aid to

navigation study. For example, the extensive investigation of maneuvering response of large vessels has been carried out at the Hook of Holland, in the entrance channels to Europort using the installed Decca chain and the "brown box" modification for positional reference. The United States has a similar capability in the VTS system in San Francisco where high definition radar capability is available for similar type experimentation. It would be a relatively simple matter to implement experiments designed to test the Mariner's perception of position based on the information available to him and compare it with the actual situations measured and recorded on the radar.

A.5 LITERATURE SURVEY

The amount of literature in the form of research reports, studies, papers presented in a variety of forums which addresses the general problem of navigation and vessel traffic control is monumental. The degree to which the generalized "process of navigation" has been examined is, however, relatively small, and confined for the most part to large ships in narrow and shallow channels.

The general objective of this report is an assessment of applicability of the recorded "state of the art" to a quantifiable definition of the process of navigation which can be used in the development of an analytic technique for the design and evaluation of aid to navigation systems. This section will therefore present an assessment of the work accomplished or in progress as reported in representative literature with regard to the application of either method or result to the objectives of the Aid to Navigation study.

A.5.1 Literature Categories

For purposes of assessment, the literature examined will be divided into five major categories, none of which can be considered totally independent of any other.

(1) System Planning and Implementation Criteria

In general, this category is composed of reports and studies of navigation requirements, evaluation methods and economic impacts.

(2) Aid to Navigation Design Characteristics

Design characteristics include those of single elements (Visibility limit standardization, optical research), element groups (design parameters for ranges, multiple aid flash characteristics), or system configuration parameters (radio navigation coverage and accuracy).

(3) Vessel Characteristics

Included in this category are studies of vessel dynamic characteristics and the effect of the results thereof on aid to navigation planning.

(4) Human Factors

Some work has been accomplished in defining workloads, the effect of fatigue and the mechanics of the vessel positioning process. Human factors also includes those attempts to determine the "why" and "how well" of actions taken under certain defined navigational circumstances.

(5) Collision Avoidance/Marine Traffic Systems

This category includes primarily system and hardware design efforts directed toward Collision Avoidance and expeditious passage through crowded, confined waters. Vessel traffic systems, traffic distribution analyses, routing schemes, etc., all fall within this category.

The thrust of the discussions to follow bear re-emphasis. There seems no benefit in a simple repetition of information contained in the bibliographic material and, in fact, a bibliography has been generated and updated as a separate effort of this study. The purpose of this section of the report is to assess the state

of the art, as represented by the literature examined for applicability of method or result to the present and ongoing studies. The questions to be answered include:

(1) Are validated methods or results available which will serve as useful inputs to the development of the aid to navigation analytic design and evaluation technique, and/or the process of navigation model?

(2) Is documented expert opinion available and equally applicable?

(3) What remains as apparently unexplored areas of investigation which are required for the successful accomplishment of this study objective?

A.5.2 Systems Planning and Implementation Criteria

A.5.2.1 General

Very little work appears available in the literature regarding generalized system design or evaluation which approaches the scale of the Coast Guard requirement, particularly with respect to audio/visual systems. There is justification for this apparent lack of activity. The following data is extracted from IALA Bulletin #55 of April 1973 reporting on 1971 data.

	U.S.	World	U.S. %
Buoys (lighted & unlighted)	25,318	40,747	62
Fixed Minor Lighted Aids (< 100 cd)	11,421	15,307	75
Floating Lights disestablished	284	307	93
Floating Lights established	325	451	72
Unlighted Aids disestablished	665	831	80
Unlighted Aids established	908	1,041	87

It seems apparent that the lack of applicable studies by equivalent authorities elsewhere simply stems from the lack of system management problems approaching the number of those facing the U.S. Coast Guard.

A.5.2.2 Integrated System Planning and Requirements

The literature reveals a few efforts directed toward the determination of a general requirement and development of planning criteria:

The following are considered examples of the state of the art.

A.5.2.2.1 Navigational Aids in Harbors and Port Approaches (Research Committee, National Ports Council of the U.K., 1972)

Of particular interest in this study were the statement of work areas and the definition of the "process of navigation," of interest not only because of the close correlation to the language of the Coast Guard study, but in view of the tone of the conclusions as representative of the "state of the art."

(1) Defined Work Areas

(a) Survey of aids available and under development, both shipborne and land-based, with a view to assessing their particular application to navigation in harbors and their approaches.

(b) A systems analysis of the available aids suitable for such navigation including an analysis of the interaction between the various types of aids in these conditions.

(c) A preliminary cost/benefit study of the value of aids in harbors and harbor approaches in assisting the free movement and turnaround of ships and in avoiding collisions and strandings.

(d) A study of the application of the considerations arising from the above in particular in relation to Port Advisory Services.

(e) Comparison of typical U.K. Port Advisory Services with that in certain foreign ports.

(2) Process of Navigation Description

(a) Where is he precisely?

(b) How is his vessel behaving?

(c) How should he get to his destination?

(d) Is he in any immediate danger?

(3) Information he requires

(a) Position Fixing

(b) Vessel Dynamics

(c) Route Planning

(d) Collision Avoidance

In spite of a lengthy "analysis" and technical description of port operations systems and cost factors, the general recommendations as presented in the management summary reveal that answers continue to be elusive. One of a number of recommendations resulting from the study includes the statement, "It is important to be able to compare the safety and delay levels of one navigational aid system with another. Further work is required before we are in a position to do this."

A.5.2.2.2 Study of Maritime Aids to Navigation in the Short Distance Maritime Environment. (Geonautics — study accomplished for USCG, 1968)

The Coast Guard has itself reported efforts to advance the aid to navigation state of the art, the cited study being a direct example. The study objectives are given on the following page.

(1) Determine the currently available aids to navigation applicable in the short distance maritime environment, and the expected state of the art (emphasis added) in the next 10 years.

(2) Describe operational characteristics and establish costs for the various navigational aids.

(3) Develop a methodology for determining the effectiveness of navigational aids systems and elements thereof. (Emphasis added)

This is the largest scale effort found by SCI (Vt) in the literature directed toward the current objective. The study resulted in a computer program based on the following approach:

"The capabilities of a component are compared with the corresponding navigational requirement of a user, and if all the capabilities meet all the requirements, the user is considered satisfied."

During the course of the study, system users and requirements were specified and aid components and subsystems examined. The study made the first attempt to assign a navigational accuracy to buoys, i.e., in rivers and channels the available accuracy is specified as one-fourth the channel width.

While the objectives and language closely correlate to the present effort, the Geonautics study involved no "Process of Navigation" as such and imposed no sophisticated modifiers (diurnal, environmental). The results depended upon the validity of the assumptions.

A.5.2.2.3 Coastal Navigation Systems Study for the General Lighthouse Authorities (EASAMS LTD – August 1977)

This study has been cited previously in this report as being indicative of the capability of EASAMS Ltd in navigation and research. (See section 4.4.2.) The methods used seem applicable to the current effort to a large degree. EASAMS describes a navigation system in terms of three parameters:

(1) Effectiveness

(2) Adequacy

(3) Utilization

and then proceeds to describe probabilistic methods for quantitative definition of these parameters. The report is lengthy and detailed in its approach. No general summation of its content is possible here other than to cite the objective of the method of development, i.e. to enable the General Lighthouse Authorities to assess the "effectiveness of the systems they provide". The study considers the relationship among systems provided, general requirements in terms of accuracy, and user equipment including radio navigation and radar. The report does not address the process of navigation from the human factors viewpoint nor does it speak in any great detail to in-harbor aid configurations such as buoyed channels.

In summation, SCI personnel are impressed with the definitions and methods proposed in this study and consider that the approach defined, subject to the necessity of acquiring additional data on the "man in the loop," might very well be applicable to the current Coast Guard effort.

A.5.2.2.4 Problems Arising from the Navigation of Large and Very Large Ships in Narrow Channels and Port Entrances (IXth International Conference on Lighthouses and Other Aids to Navigation - Ottawa 1975)

The literature is relatively fruitful in describing the planning processes and results for the special cases epitomized by the title of this reference. The drawback to much of the work when considering applicability to the generalized navigation problem lies in the restrictive nature of the areas of study. The reports deal with particular ports, with specific channel configurations

(lengths, bends, etc.), with particular ships. The previous section cited two examples of such work accomplished by the EASAM Company (Study of Systems of Aids to Navigation in the Approaches to the Port of Gravelines), (Definition Des Aides Radio Electrique Aux Approaches D'Antifer). The report referenced here is a third example of a paper addressing the large ship problem. The report is cited since it discusses the problems exactly in the same terms as are being considered in the Coast Guard study, i.e., aspects of channel width, vessel characteristics, vessel aspects, and environmental conditions directed toward specification of an aid to navigation system. Certain conclusions are of interest:

(1) For large vessels, a response time of at least 2 minutes to any change in conditions (rudder angle change, engine speed change) must be considered.

(2) The effective width of the ship must include the "drift" (crab angle) when considering accuracy of positioning within a channel.

(3) There is a danger of grounding on bows, in the direction of cross current, or stern when attempting to "crab".

(4) Conventional aids (visual) are not accurate enough for channel navigation for the types of ships being considered. Along track accuracy may be satisfactory (10-20 meters), but cross track position, because of high wheelhouse, ship width, etc., is probably no better than 50 meters. A $\frac{1}{2}^{o}$ range open angle represents 50 meters at a distance of 6 km. This is not sufficient to meet the proposed 10-20 meter requirement in both along and cross track position.

(5) Minimum required navigation information is along and cross track position (10-20 m accuracy), along and cross track velocity (¼ knot accuracy). Along track position is required because the time to the next maneuver must be accurately estimated.

This paper can be considered representative of the state of the art in specific port planning. The process of navigation parameters cited appear representative of current opinion and study results. Additional support is found in a paper entitled "Technological Considerations in the Design of Future U.K. Harbor

Systems" (The Hague Symposium - 1976) with the following requirements which the paper postulates can be accomplished with on-board radar systems.

Distance Accuracy	.01 NM (∿ 20 meters)
Speed	.25 knots
Offset	30 feet (∿ 10 meters)

A.5.2.2.5 Costs and Benefits of Navigational Aids in Ports: (R. O. Goss) (Chapter 7 – Advances in Maritime Economics, Cambridge University Press)

As the final step in surveying "planning and implementation" literature, the subject of cost-benefits was considered. A number of reports attempt to statistically relate costs of port services (including navigation systems), traffic statistics (costs of delays, etc.), and casualty analysis. Chapter 7 of R.O. Goss's* book seems representative of the most modern and sophisticated analytical technique. The approach is a relatively rigorous mathematical analysis. The introduction and conclusion of the cited chapter, quoted in their entirety on the following two pages, yield an indication of the scope of the technique.

> Introduction
>
> The increasing density of marine traffic associated with the continued growth of seaborne trade presents increasingly difficult problems for those concerned with movements in port approaches. These are further exacerbated by ships being, on average, larger and therefore less maneuverable. The frequency of collisions is increasing and the movement of vessels is often slowed by poor visibility or by the necessity of avoiding collisions. The scientific, technological and operational difficulties involved are, of course, fundamental and it is natural that most studies deal with these aspects of the subject. But any equipment or regulations that may be developed must affect, directly or indirectly, the use of the community's real resources and, insofar as these resources have alternative

*"Costs and Benefits of Navigational Aids in Port Approaches," R. O. Goss.

uses, they impose costs on the community as well as providing benefits. There is no a priori reason why marine navigation and control systems should be excluded from considerations of the efficient overall distribution of national resources. The sums involved are substantial: over 8 mn per year is spent on lights in the British Isles excluding those financed by port authorities and much more on other private and public navigational aids.

There is, however, little experience or literature in this field and that dealing with similar problems elsewhere (for example, concerning roads and aircraft) suggests that the economic techniques required are by no means straightforward. The object of this paper, therefore, is to provide some discussion of these techniques in this context. For reasons that will already be obvious, much of what follows rests partly on work done in other fields.

Conclusions

The appendix has attempted to outline a practical solution to the problem of measuring the benefits of a navigational aid when some or all of those benefits are not appropriated by the operating authority, through charges for the use of the facility. In the first section it was suggested that a good approximation to the size of this benefit can be obtained by calculating the change in the f.o.b. value of exports and the c.i.f. value of imports induced by the cost reductions associated with the navigational aid. The second section outlined a model which enables these effects to be calculated for any initial change in costs and for a range of values for supply and demand elasticities. In practice, we would need to take into account factors which have not been explicitly considered above. For example, it is unlikely that even under competitive conditions the benefits of an aid would be passed on immediately. Therefore, some estimate would have to be made of the lag between the installation of the aid and the time by which the competitive process has fully worked itself out and the cost reductions have been passed on. During this intervening period the conclusion stated earlier, that it was immaterial whether the initial beneficiaries were British or foreign ships, is no longer valid. Doubtless, an actual study would throw up special problems which had not even been foreseen. Nevertheless the basic methodology outlined above would still be valid, and would provide a means of obtaining estimates of the benefits of an aid.

A.5.2.2.6 Summary

Representative samples of existing literature relating to planning and implementation of aid to navigation systems have been discussed. With certain exceptions, particularly in the area of method (General Lighthouse Authority Report), it does not appear that material applicable to the large scale, general aid to navigation issue is available. Analytical techniques have been developed for definition of requirement (Problems Arising from..... Large and Very Large Ships) but their systemwide application seems limited, in particular due to the variety of ships and boat types impacting on the Coast Guard's responsibility. Based on the survey, it would appear that the "state of the art" of application of analytic techniques to large scale, integrated aid to navigation systems will be significantly advanced by successful conclusion of the Coast Guard's present efforts.

A.5.3 Design Characteristics

A.5.3.1 Audio/Visual Design Characteristics

A significant amount of the literature deals with design characteristics of aids to navigation and ranges from the hardware involved (optical research, recognition characteristics) for single aids through examination of coverage and accuracy of wide area radio navigation systems. The primary area of interest, for purposes of the current study, is the application of defined operational parameters of particular aid types to the problem of system evaluation. For example, Section A of CG222-3 defines such operational parameters for standard Coast Guard Buoys in terms of visual range and radar range based on certain assumptions regarding height of eye, meteorological visibility, antenna height, etc. Such standards are the result of research efforts appearing throughout the literature and, if the parameters are acceptable, there seems

no benefit in a repetition of the research work upon which they are based. If they are not acceptable, the current study is intended in part to determine the reason. Nowhere in the literature do we find any report of a design study resulting in a significant re-configuration of existing audio/visual aids. Lightships have been replaced with light stations or large Navigation Buoys, manned lights have been automated, but the thrust of such effort has been economic rather than operational, i.e., the process of navigation is unaffected by the difference between a light being manned or unmanned. It is therefore considered reasonable to state that the state of the art in terms of audio/visual aid characteristics is represented by the standards delineated in CG-158 (Light List) and CG-222 (Aids to Navigation Manual). The application of the supporting research, such as that seen in the report "Probabilities of Detection and Identification of Navigation Buoy Light Signs" (David W. Taylor Naval Ship Research and Development Center – February 1977) remains to be defined by the current study, particularly with regard to the psychological and physiological aspects of the detection and identification problem.

The literature does view with some concern the philosophy of danger marking using visual aids, particularly in the choice between lateral and cardinal marking systems. The article "The IALA System of Buoyage" published by the London Dock and Harbor Authority (May 1977) describes the current results of the work of the Buoyage Committee of IALA, and the institution of the so-called IALA "System A" (Combined Lateral and Cardinal Marking) in Northern Europe. Interesting background material on the marking systems is found in a paper presented before the Honorable Company of Master Mariners, in London, by Captain J. E. Bury of Trinity House (Chairman of the IALA Buoyage Committee) and in the minutes of the discussion following the presentation. Since ultimately the process of navigation involves the "perception" by the mariner of information presented by the aid configuration

and marking, current opinion as reported in such papers is a matter for consideration in the present study.

A.5.3.2 Radio Navigation Systems

The literature dealing with radio navigation techniques presents examples of analysis which, given the same information, would be equally applicable to audio/visual systems. If one could define the mariner's "perception" parameters to the degree that the parametric capabilities of radio navigation receiving equipment can be defined, and if the "coverage area" and accuracy of information of a visual aid could be described in the same fashion as, for example, a Loran or Decca coverage area, then quantification of the design and evaluation of the audio/visual technique would be immediately practical. The analogy extends to the "guidance" mode provided by a marked channel. The study by EASAMS Ltd. (previously cited): "Definition Des Aides Radio-Electriques Aux Approaches D'Antifer" is an example. In this study, the requirement for and accuracy of information were defined, electronic systems identified which were capable of quantitative evaluation of requirement satisfaction capability and the unit with which the required information was to be presented were established. Whether the numerical values presented are generally applicable is a matter for further analysis. What does seem applicable to the current effort is the methodology used for definition of those parameters. If the study, in defining the process of navigation, can develop definitive measures of information available and accuracy of perception for audio/visual systems, then the analytic method as exemplified by the Antifer Study may be applied.

Techniques for evaluation of wide area coverage for positioning via radio navigation means have been accomplished in great detail by a number of authorities. Such studies usually are involved with an examination of alternatives based on accepted

system operational parameters. The method involved would also be applicable to large area audio/visual coverage if the operational parameters can be standardized and accepted. Examples of such detailed analyses include the "Rustad Report" (Norwegian Joint Signals Administration – 1960) resulting in the national implementation of an integrated radio system composed of Consol/Decca and the extensive studies accomplished by the Coast Guard in the early 1970's (Decca, Loran-C, Differential Omega) resulting in the establishment of Loran C as the standard Coastal Confluence System for the United States. In the "micro" coverage area, studies of radio techniques have been carried out to establish applicability of special purpose radio techniques (examples – Differential Loran C Time Stability Study (USCG, 1973); Differential Omega Studies (USCG, 1966); the "COGLAD" experiment, etc.). As with the previously cited documents, whether the results of these efforts are applicable to the current study remains to be seen. The method of approach in determining the operational parameters of the configurations examined seems generally applicable.

The last area in which one finds "applicability" in the radio navigation literature is exemplified by the study "Termination of Loran-A, an evaluation of alternative policies" (Oregon State University, October 1977). This report deals with the disestablishment of an aid to navigation with replacement by one deemed operationally (and economically) superior, and represents the only information which appears in the literature which discusses factors involved in an aid reconfiguration and the potential impact on the mariner.

The preceding paragraphs make no attempt to evaluate radio navigation system design parameters as they might apply to the requirements of the navigator. This literature survey was initially identified as involving an assessment of information available therein for applicability to the objectives of the current study, specifically for development of analytical methods for system

design and evaluation. The literature reveals that, in the radio navigation area, such methods are available and have been extensively used. No such methods have seen significant application in the audio/visual area. This can be attributed to the fact that the methods depend on operational parameters which, to a large extent, remain undefined for audio visual aids. Hence, we conclude that from the point of view of the state of the art, analytic methods are available. What remains to be done is the definition of the input parameters thereto.

A.5.4 Vessel Characteristics

The General Lighthouse Authority Study (Section 5.2c) suggests quite reasonably that adequacy criteria for aids to navigation be based "on the accuracy requirements of the most demanding non-specialist user of the sea area under consideration". In restricted waters the criticality of such parameters as channel width, positional accuracy, information timeliness are significantly magnified for very large ships due to maneuvering characteristics and vessel profiles of a sort not previously experienced. Extensive research is reported in the literature with regard to such characteristics, and additional parameters in the process of navi gation "equation" seem indicated in such cases which exemplify the currently "most demanding situation."

Examination of the literature would seem to indicate that vessel hydrodynamic characteristics can be described mathematically to any degree of sophistication required. The work of H. Eda (Vessel Maneuvering Simulation - 1976) presents a mathematical model of the process capable of execution on a digital simulator. However, verification of such models is considered a requirement and both model basin and experimentation under real life operating conditions seems to be a continuing requirement. The Proceedings

of the First CAORF Symposium, June 1977, speaks to the problem of obtaining shallow water hydrodynamic coefficients.

A realistic series of experiments directed toward acquisition of such data was observed by members of the SCI (Vt) staff during a visit to the Netherlands Ministry of Transport and Public Works, "North Sea" Directorate, with a subsequent tour of the facilities of Europort, of the Hook of Holland, a large scale VLCC terminal. Using the installed DECCA system as a navigational reference, individual vessel data is acquired during the approach and docking phase, with the following being recorded each minute:

(1) Ship's Head

(2) Speed

(3) Leeway

(4) Rudder Angle

(5) Keel Clearance

(6) Engine RPM

Examination of the strip charts which graphically present the data as a function of position verifies the postulations in other papers regarding the significant time lags encountered between the imposition of a control command (Rudder change, RPM change) and the actual vessel response thereto. The question of response time is also addressed in the paper "Problems Arising From Navigation of Large and Very Large Ships in Narrow Channels and Port Entrances" (Dumas, Ninth IALA Conference, 1975) wherein a time lag of at least 2 minutes must be assumed as inertial delay.

The above cited paper also deals at some length with channel parameters and requirements for navigation information. The recommendation of a commission of the Permanent International Association of Navigation Congresses for a channel width of at least 5 times the ship's width is mentioned. This recommendation,

of course, is intended to apply to channel design. However, its converse may serve to define the size of a ship entering an established channel and hence could be considered applicable to the current study. The "Problems Arising........" paper continues with the presentation of additional discussion of applicable parameters including a reaffirmation of the position reference point (Center of Gravity) and the minimum information required from the navigation system (along and cross track velocity).

The literature on the large ship studies (aside from theoretical hydrodynamics) discusses the need for information, the form of the information, and channel diversion relationships (such as the 5/1 channel width to ship width mentioned in the previous paragraph). In the studies of EASAM'S LTD, it was pointed out that two parameters not normally considered in general aid to navigation planning, must be taken into account in dealing with large ships.

A.5.4.1 Reference Point

When dealing with large ships, it is necessary to define the location aboard ship to which the measured or "perceived" position is referenced, since most corrective action will be based on that position. The choice, verified in other papers, seems to be the Center of Gravity, which, it is suggested, can be estimated (if unknown) by a position of ½ LOA. Due to the length of the vessels involved, the angle of bow and stern may be changed with respect to the channel direction without a similar change occurring with regard to the direction of travel of the center of gravity. Dumas (previously cited) suggests the ultimate requirement for more than one position sensor (perhaps bow and wheelhouse) to more closely define the situation.

A.5.4.2 Effective Ship's Width

In defining the accuracy of information required to maintain a vessel within a channel of specified width, the effective ship's width must be considered. Except in situations where no cross channel effects are present, this width cannot be assumed to be the ship's beam, but rather a parameter defining the width of the lateral section of the channel "swept out" as the ship proceeds. Instantaneously, this can be described as

$$\text{length } (\sin x) + \text{beam } (\cos x)$$

where x is the crab angle. Dynamically, as described by EASAMS, this equation becomes more complicated. This parameter plays a large part in accuracy determinations when considering a large ship in a proportionately narrow channel. L. A. Moele, in his paper "Behaviour of Large Tankers in Shallow Water in Relation to the Dimensions of an Approach Channel" (Symposium on Offshore Hydrodynamics, The Netherlands, 1971) presents an interesting set of data regarding the problem of drift ("crab") angle in the presence of a transverse effect as follows:

Ship 200,000 Dwt: Depth to Draft Ratio 1.2 Cross Current 2 Knots

Along Track Velocity	Drift Angle	Rudder Angle	"Effective Width"
10	~11° (port)	8° (starboard!)	104 meters
5	~22° (port)	~7° (starboard!)	157 meters

A.5.4.3 Timeliness of Information

A parameter previously mentioned, but worthy of re-emphasis, is the timeliness of information. The impact of this on aid design is significant when considering that a control command (rudder angle, engine speed) must be made in the order of minutes prior to any responses from the vessel. While very large ships, of the order of hundreds of thousands of tons, are not an immediate

problem for most U.S. ports and harbor entrances, there are nevertheless many situations where ships large in proportion to channel width and maneuvering area exist. The methods of study presented in the literature for recent VLCC ports may very well be applicable in a scaled-down form, in the current development of the process of navigation model.

One final reference will be cited here as the only mention found in the literature involving a probabilistic approach to channel maneuvering. "A Stochastic Model of Ship Maneuvers" (Hermans-Delft University of Technology, Netherlands Ship Model Basin) presents the approach. Starting with the presentation of "Buffons Needle Problem" which states that

$$P_G = \frac{4T}{\pi C}$$

where P_G = geometric probability of hitting channel walls

T = stopping distance

C = channel width

the existence of additional dynamic factors is examined and a mathematical model, for a straight channel which develops a probability of departing the channel is presented.

A.5.4.4 Summary

Although the large majority of published effort in recent years has been directed toward the examination of the behaviour of and navigational requirements for very large ships in restricted channels, it is considered that much of the method and parameter definition is applicable to the current effort, specifically:

(1) The necessity for establishing the most desirable reference point aboard ship

(2) Minimum information required relative to that reference point(s)

Along Track Velocity
Cross Track Velocity
Along Track Position
Cross Track Position
Rate of Turn (and yaw)

While the studies have developed quantitative accuracy requirements for the above based on maneuvering characteristics* of very large ships, the "perception" of such parameters including the accuracy thereof are an input applicable to the process of navigation at any level.

(1) The necessity to consider the timeliness of information. The buoy marking the turn may not be enough. A requirement may exist for a buoy x yards, or x minutes (at channel speed) prior to the turn to trigger the necessary control command, accounting for inertia.

(2) The difference between ship's beam and its "effective width" in developing accuracy requirements for cross track positioning information.

A.5.5 Human Factors

An examination of representative samples of the literature addressing "Human Factors" reveals that only recently, with the use of large scale simulation, have experiments been initiated which will contribute significantly to an understanding of the mental processes involved in decision-making in the process of navigation.** Some examples of the types of approach reported are listed on the following page.

---

* Example of Accuracies cited:
Along Track: 10-20 meters
Cross Track: 5-10 meters
Along and Cross Track Velocity: 0.1 meters/second (0.2 knots)

** Appendix E of this report discusses in detail a modern human factor approach to problems of the type under study by the Coast Guard.

A.5.5.1 Mental Load Induced by Handling a Large Ship – C. L. Truijers, Netherlands Ship Model Basin. (Symposium on Shiphandling; Wageningen, the Netherlands, 1973)

This experiment established three navigation situations involving a turn between two straight channels, with navigation information provided by a "leading line" system. The three problems involved an angular bend and two curved bends of different radii. Subjects made the runs after a night without sleep and during the runs, such variables as heartbeat, EEG, skin conductance and horizontal eye movement were recorded. The report claims no new information regarding the navigation systems themselves. Heartbeat data seemed to definitely indicate a lesser required effort on the part of the pilot, however, in maneuvering a long curved bend, as opposed to a sharply curved or angled bend.

A.5.5.2 Human Factors in Ship Control – Functions and Information Requirements of Deck Watch Officers and Other Personnel – Mara

This report presents a detailed description of the mechanics of navigation in restricted waters including sources of information input (but not quality of information or method of derivation). The results of such a study are conceivably applicable in the definitionof a process of navigation model in defining workloads. Little attention is paid, however, to the mental operations performed or the information-evaluation process upon which decisions are based.

A.5.5.3 Pilotage in Confined Waterways of the United States, a Preliminary Study of Pilot Decision Making – Huffner

This ambitious project involved "on-the-scene" audio (with, in some cases, accompanying video) taping while a pilot actually conned a vessel through a harbor area. A continuous narrative of actual commands and rationale, therefore, with comments on the process, was recorded for a number of harbor areas under a variety of

operational situations. The technique lends itself to a qualitative "feel" for the process of piloting, but does not appear to lend itself to the development of quantitative parameters for input to a model of the process of navigation. The method may have some value in model verification, but would require a highly structured approach on the part of the process recorder and a careful selection of both area and subject. One pilot, during an interview with SCI personnel, indicated his belief that a tendency might exist for the observed subject to "play" to the problem rather than proceed in his normal manner.

A.5.5.4 Experimental Reports from the Maritime Administration's Computer Aided Operations Research Facility (CAORF)

As the most sophisticated ship simulation system in the world, CAORF is capable of providing a basis for experimentation on "Human Factors" unequalled by any other research facility. An examination of reports currently available, specifically from those of the first CAORF Syposium (June 1977), reveal an emphasis toward collision avoidance behaviour. However, the as yet unpublished Restricted Waterways Experiment is expected to yield results which are immediately applicable to the development of valid data regarding the accuracy of positional information provided by selected aid to navigation configurations. It is of interest to note that many of the questions to be asked of the experimental subjects correspond to those posed by SCI in the course of conducting expert interviews.

The tremendous advantage accruing from the ability to ask these questions while the subject is actually performing the processes involved is obvious. It will be interesting to compare the results with those obtained via the interview process.

A.5.5.5 Summary

The state of the art in human factors research, as represented by the literature surveyed, seems reasonably capable of responding to the question:

How?

There are large gaps evidenced, however, when the question:

How well?

is posed, at least to the extent that the answers can be directly applied to the development of an analytic aid to navigation system design and evaluation criteria based on defined "process of navigation" model. The effort described in Section A.5.5.4 will serve to fill those gaps to a large degree.

A.5.6 Collision Avoidance/Marine Traffic Systems

It would appear, from a review of literature relating to vessel navigation, that the single largest subject area addressed in recent years is that of Collision Avoidance and the related area of Marine Traffic Systems. Unfortunately, it also appears evident that the work reported is minimally applicable to the objectives of the current Coast Guard Study. Aids to Navigation in the classic sense are not intended to serve the cause of collision avoidance as an implementation objective except perhaps in marking tracks associated with traffic separation schemes. There is no indication that risk of collision can be significantly affected by design of an aid configuration (although the opinion has been expressed that gated pair marking as opposed to single line in some areas has a tendency to "funnel" traffic). It is only recently that Marine Traffic System technology in any form has been considered as an "aid to navigation" within the purview of the Coast Guard's statutory responsibility. The potential effect of concepts such as VTS (Vessel Traffic Systems)

AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7

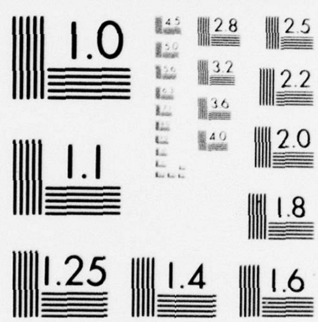
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)

MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A

UNCLASSIFIED USCG-D-38-78 NL

4 OF 6

AD
A059891



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

or Harbor Advisory Radar on configuration management of Audio/ Visual systems is undetermined. A possibility exists that the results of the current Coast Guard study may indicate the desirability of examining the implications of a reconfiguration of audio/ visual aids within the coverage area of an operating Marine Traffic System, but no such activity appears in the current literature.

The literature addressing the specific problem of Collision Avoidance is broad in scope and includes Human Factors, Radar Plotting Techniques, Optimization of Maneuvers, ship dynamics, equipment evaluation, threat assessment and traffic distribution studies. Certain approaches, specifically the "ship domain" concept proposed by Fuji in Japan and Elizabeth Goodwin in the U.K., have been cited as possibly extrapolatable to positioning requirements in channels. We believe this would be difficult. In fact, our conclusion regarding the literature on Collision Avoidance techniques is simply that there seems no application of the presently reported work to the objectives of the Coast Guard Study. What is lacking is an examination of collision avoidance maneuvering in restricted (in width and depth) waters and channels as an element in the total process of navigation. Results of some of the experiments now underway or proposed may yield this information but it appears currently unavailable.

The question of the applicability of Marine Traffic Systems is less clear cut. There appears to be some opinion that the "control tower" approach, at least for large ships in restricted terminal areas may be more effective and hence may eventually obviate the need for audio/visual or even general purpose electronic aids in these specialized circumstances. Current system design is described in detail in the literature, specifically in a series of papers presented at the Marine Traffic Systems Symposium held at the Hague, Netherlands in April 1976. Technical specifications for current and/or future installations for at least nine different ports were discussed. Two points are clear with regard to such

installations. First, the technical designs must obviously be tailored for the specific harbor and its traffic type. Secondly, the degree of control authority, as well as the form of the service provided, varies widely.

The most basic systems found simply provide port information which may or may not be associated with shore-based radar. In some cases, port operations involving pilots, tugs, berths, etc., are centrally coordinated by the port authority through its information system. The next level of operation involves the provision of information based, in part, on radar derived data. Such systems, exemplified by the *San Francisco System*, provide information only, with no situation interpretation or navigational advice provided. The philosophy is clearly presented in the investigation and review proceedings for the Oregon Standard/Arizona Standard collision in San Francisco harbor. In their most comprehensive form, traffic systems with shore-based radar input, operated by qualified Masters and/or Pilots have the authority and duty to control traffic and, if it appears to the operator that a dangerous situation exists, may restrict movement or direct a ship not to make a proposed passage.

A comprehensive listing of Port traffic services is contained in a compendium prepared by "Summary of the First Survey on Marine Traffic Management and Information Systems..." (Electronic Navigation Research Institute, Ministry of Transport, Japan - June 1977). This work presents the operational details of the services in terms of operator qualifications (Master, Pilot, Military), port communications, navigation information and port services available, etc.

In summary, the literature abounds with statistical methods of traffic distribution study; optimization of collision avoidance equipment and techniques; methods, equipment, and systems for radar based traffic systems, etc. The state of the art, while relatively advanced in the areas described, does not seem immediately applicable to the defined objectives of the current Coast Guart study.

282 blank

APPENDIX B
INTERVIEW QUESTIONS AND COMMENTS

This appendix presents the questions which were developed by SCI (Vt) for use in expert interviews and discussions. The answers present, in summary form, a best representation of majority opinion. During the course of the interview process, a number of comments from interview subjects were received. As explained in Section 3 of the report these comments are considered valuable in acquiring some feel for the type of dialogue which might become a valuable part of the Phase II effort. The specific port comments are presented in the second section of this Appendix.

B.1 INTERVIEW QUESTIONS AND ANSWERS

B.1.1 Channels

(1) Q. How do you estimate your vessel's alignment in a channel? In what manner?

A. The vessel alignment in the channel is done both by the ship's compass and the aids to navigation present. If there are ranges and buoys, vessels will use both as an alignment guide. If neither are present, they must use other means such as shore aids, particularly with radar. The latter usually happens in an ice season.

(2) Q. Do you use aids astern as well as ahead?

A. The use of aids astern is not as regular as the use of aids ahead. Many vessels do not use them at all. When leaving the harbor many of the ranges are astern and they are not readily visible. New, modern vessels, such as VLCC's, have all around bridges; and, hence, they are more apt to be using the aids astern.

(3) Q. Do you use ranges? Day, night, fog, astern. What is the maximum distance you use the range?

A. Ranges are used to the maximum extent practical by all navigators. The range is one of the main sources of information particularly in small segments of channels where no other aids can give as much information. The maximum distance that they are used depends upon the number and location of other aids. In channels which are buoyed very heavily and also have ranges, the use of the range becomes secondary. In lightly buoyed channels, ranges are considered the primary aid and are used to the limit of the straight channel. The majority of ranges, since they are shore-based, cannot be used in reduced visibility.

(4) Q. In navigating a buoyed channel, do you specifically use the channel centerline, or the channel boundary as your reference? In general, what is your measurement (estimation) procedure?

A. Generally, the vessels try to maintain a position just to the right of channel centerline. This depends upon the size of the vessel; the larger the vessel and deeper the draft, the more he will be concerned with staying just to the right of centerline. A smaller vessel will tend to favor the starboard side of the channel a little more, giving room to the larger vessels as a passing situation occurs. The primary method of determining position within the channel is a measurement of the distance abeam of aids as they pass each aid. The position references when they are between aids are the angles perceived between the nearest two aids ahead. Everyone is conscious of an imaginary boundary on the side of the channel, but an exact method of measurement to that boundary was not defined by any of the masters or pilots.

(5) Q. Under normal conditions of weather and visibility, no traffic, and a uniform depth channel, would you normally adjust the ship's track to recover the centerline if you perceived that your track were displaced from the centerline but parallel to it?

A. Large ships normally try to regain the center of a channel unless they are coming to a point where a change in the channel configuration will occur. The alternative is to come to the right in a passing

situation. Again, their intended track is not necessarily the centerline, but generally just to the right of centerline, frequently stated as one beam distance off the centerline when in a narrow channel and up to 2 or 3 beam-widths in a wide channel.

(6) Q. What is the minimum deviation from desired track before you make a correction?

A. The distance from the channel centerline that causes mariners to become uncomfortable is situation-dependent, with 50 feet being the limit for larger vessels. Most answers indicated that mariners would tend to return towards their intended track just as soon as leeway is apparent or when two beam-widths off their intended track. In certain areas of the country where there may be a softer bottom and the channel does not have very steep boundaries, they consider the situation less critical. With no wind or current, they may elect to make the trip fairly close to the bank with no fear of danger.

(7) Q. At what distance from the channel boundary do you become uncomfortable? Panicked?

A. Most masters have stated they never want to be any closer than 50 feet from the channel boundary. They have never been able to state a panic distance in terms of feet because the attitude of the vessel is a significant input to the navigation thought process.

(8) Q. What is the maximum rudder angle you would use in an uncomfortable position? Panicked?

A. The maximum on a rudder angle which is used depends on the vessel size. For vessels up to the 10,000-ton class in a normal run, very seldom do they use more than 15°. VLCC's are always apprehensive of setting up an unstoppable swing and therefore they use no more than 15° if they can avoid it. In general, the larger the vessel, the less tendency to use high values of rudder angle, except for turns.

(9) Q. In passing between paired buoys in a channel, how accurately do you feel you can estimate your offset from the centerline based upon an estimate of the distance to the buoys abeam?

A. In estimating the distance off-set from the centerline based on the estimate of the distance of the buoy of the beam, many mariners state that they can do this to an accuracy of one beam width. Other opinions state that the wider the channel, the less they are concerned with exactly how close they are to the centerline, but also the less accuracy they feel they can achieve in this measurement process.

(10) Q. How do you do the estimation when you are midway down the channel between sets of buoys? To what accuracy?

A. Under normal visual operating conditions, mariners estimate the centerline distance by the difference in bearings to the buoys ahead. VLCC's felt that they could estimate the accuracy to be two to three beams, depending on the spacing of the aids. No clearly understood relationship between aid spacing and estimation accuracy seemed to exist.

(11) Q. How do you do the estimation when the buoys are staggered?

A. The larger the vessel, the more frequently radar will be used when the buoys are staggered. On vessels up to 80,000 tons, they are still doing visual estimation and believe they have a tendency to zig-zag a little bit more, heading towards the nearest buoy.

(12) Q. How do you do the estimation when only one side of channel is marked?

A. When only one side of the channel is marked with buoys, estimation accuracy is believed to be somewhat reduced but not to any significant degree. The process is the same; they estimate the distance off of buoys when they are abeam and they estimate the distance to the intended track by visual observation of the bearings of the aids ahead.

(13) Q. In estimating your position and track in a channel, do you use the perceived alignment of the buoys astern as well as ahead?

A. Very seldom are buoys astern used to perceive the vessel's alignment.

(14) Q. In running a buoyed channel, with gated pairs of buoys, how many pairs ahead do you estimate you need to satisfactorily estimate your position within the channel? Does buoy spacing make any difference?

A. Most mariners prefer to have two pairs of buoys ahead whenever feasible. The same opinion applies to channels that are buoyed on one side. Buoy spacing does make a small difference, but most mariners believe that buoy spacing should be proportional to channel width. Europeans have a reference of 4 to 5 times the width which seems to be the generally accepted factor by masters and mariners.

(15) Q. Would the same number of pairs divided between ahead and astern provide the same capability?

A. When the same number of buoys are divided ahead and astern, there is not the same capability of measuring position. Most people prefer to have the buoys ahead so that they get perspective angles more effectively.

(16) Q. How do you use a fairway buoy?

a. Attempt to pass at a specific range when abeam even if a course alteration is necessary?

b. As a general reference for position estimate?

c. Can a fairway buoy replace or obviate the need for other aids in its vicinity?

A. In passing a fairway buoy, most mariners try to pass it at a specific distance when the vessel is abeam, even if a course alteration is necessary. The smaller the vessel, the less relevant the entrance buoy or fairway buoy becomes. The fairway buoy is used primarily as guidance for alignment with the channel. The buoys along the channel give the guidance to enter the channel. By observing the rate of turn to enter a channel, a pilot who has just boarded the vessel begins to obtain the first feel for the maneuvering characteristics. In addition, during this approach, the effects of wind and current are estimated to ascertain crab angle.

(17) Q. In a head-to-head meeting, if both ships are on the centerline, at what range would you normally alter course for safe passing? What would be the minimum range?

A. In a head-to-head meeting situation, most ships on the channel centerline change course when they are two to three ship lengths apart, with the minimum accepted being two ship lengths. The larger the vessel generally the longer the separation, even in terms of ship lengths. European conditions usually indicate three to four ship lengths before they make the break.

(18) Q. What is the maximum rudder angle used in passing for a meeting situation?

A. Maximum rudder angle used in passing is undefined. It varies with speed. Some mariners have stated they seldom need more than five degrees. Others with slower vessels in narrower channels may use 10 to 15 degrees. Again, it is highly dependent on the vessel speed.

(19) Q. When overtaking, does the overtaken vessel move to one side of the channel?

A. When an overtaking situation occurs, the overtaken vessel generally moves over to one side of the channel. Some regulations in foreign ports require this; however, this may be in opposition to the international rules of the road.

(20) Q. Because of the bow cushion effect, do you need to adjust the ship's heading during passing by rudder angle changes? What values of rudder do you usually use? When coming out of the passing situation, do you use more or less rudder than when entering?

(21) Q. Do you use rudder angles, course changes or combinations when passing?

A. Questions (20) and (21) were not specifically answered. All answers indicated the maneuver depended upon the situation and the experience of the pilot/master to complete a passing situation successfully.

(22) Q. What are the relative positions of both vessels when you start to maneuver out of a passing situation?

A. The relative position for both vessels when they start to maneuver out of a passing situation was slightly before they arrive at a beam-to-beam situation.

(23) Q. In a channel which is busy with traffic, would you normally

a. Navigate along the starboard half?

b. Navigate on the centerline, maneuvering as necessary?

A. In a busy channel, most people still try to navigate to the right of the centerline maneuvering as necessary to avoid any collisions. They usually keep to their own water. However, in Europe, with VLCC's, all traffic is under positive shore control. The VLCC's stay strictly on a centerline as long as desired since all other vessels are prohibited from that zone.

(24) Q. In estimating the separation between vessels for meeting or overtaking, do you base this estimate on aids alongside the channel? What other criteria do you use? How do different sets of aids affect this measurement? (Staggered, one side only, etc.)

A. When possible, vessel separation in a meeting situation is estimated by known distance between aids and relative position of the vessels to the aids.

(25) Q. In a channel, if you perceived that you were off the centerline, would you take immediate corrective action (no traffic)? Would you base your decision on the angular estimate (offset of ship's head with aid alignment) or estimate the distance from the channel edge? Which of these effects would you perceive first?

A. The most frequently used information is the aspect angle of aids. This is used to give the estimated distance to the channel edge, and most mariners believe that they would perceive the angular relationship of the aids before they perceive their actual distance from the channel boundary. See Question (6).

(26) Q. Do vessels having different maneuvering characteristics affect your navigation process? How? Where?

A. Maneuvering characteristics definitely affect the navigation process. The smaller the ship, the higher the maneuverability (usually), particularly small coastal vessels that may have twin screws,

twin rudders versus the slow ponderous VLCC's. With regard to vessels in the intermediate class between 50,000 and 80,000 tons, some are considered very highly maneuverable; others are considered to be the equivalents of some of the older jumboized T-2 tanker class or the C-2 containerized cargo vessels.

(27) Q. Could you describe your thought process in estimating

a. Position within a marked channel?

b. Ship's head with respect to channel course?

c. Ship's track with respect to channel course?

d. Position within a bend?

A. This question was considered too broad in scope to permit definitive answer. The answers actually appear in other more specific areas of questioning.

B.1.2 Bends

(1) Q. When approaching a bend, how far from it do you become more concerned with the bend than your present location?

A. The distance from a bend at which mariners become more concerned with the location of the vessel as it goes into the bend is about 2/3 or 1 ship length away from the point where the turn is started. The turn is made such that the advance of the vessel will bring them to a point where the bend starts; or where the mariner wants the vessel's heading rate to be changing.

(2) Q. What are used as guides when estimating the time and location at which the turn should be initiated?

A. The guides that are used to estimate the time and location when a turn should be initiated varies among mariners - turning by eye on a selected buoy or by the perceived alignment of a pair of buoys that may mark the inside of a turn. This is somewhat dependent upon the position of the ship's bridge, i.e., whether it is very far forward or very far aft.

(3) Q. How do you adjust for vessel advance when making a bend?

A. Adjusting for the vessel advance is done by knowing what the turning radius of the vessel is, or estimating the turning radius by a pilot going aboard the vessel for the first time. Generally, the pilot has made som course corrections to the vessel before entering a bend and has a feel for the turning radius. Many of masters of the VLCC class thought that the correct rate of turn was more a matter of judgment than deliberate calculation, but they did check their turning radius at sea by radar before they actually placed their ship into a maneuvering situation in the harbor.

(4) Q. How does stern transfer affect your decisions when making a bend?

A. This question covering stern effect was not frequently answered. It did not make much of a difference unless the bend was severe. Most pilots or masters preferred positioning the vessel so that stern transfer effect does not cause any problems. This positioning is done before they enter the bend.

(5) Q. When making a turn, do you use more rudder than necessary to kick it over, or just enough to make the turn?

A. Quite frequently, more rudder than necessary is used to start the turn and then the helm is eased to insure a smooth and gentle swing.

(6) Q. How do you estimate that you are making the turn properly? Do you do it differently at night? On radar?

A. The rate of turn is estimated by visual observation of the aids ahead. The same conditions apply for radar navigation. The relative change of aspect by eye is probably the most significant.

(7) Q. How much of bend will require speed changes to kick the vessel over?

A. Speed changes are not too frequently used unless the bend is over 60° and the channel is relatively narrow, i.e., 800 feet. The only time use of such a technique was reported was in maneuvering in very restricted channels such as the Arthur Kill.

(8) Q. Is it practice to stay on the inside or the outside of the bend? How does traffic affect this?

A. Most people prefer to try to stay in center of the turn or on their own side, i.e., just a little to the right. If there is any traffic in the vicinity, they will obviously tend to stay more to the right than they would if there were no traffic.

(9) Q. In what configuration of bend do you arrange not to pass or overtake? What size vessels are involved in this no meeting situation?

A. The bends that are arranged for a no passing or overtaking situation are generally those that are narrow. Those that have a wider degree of bend, and are truncated, may be a preferred passing area. All mariners in the harbor who are moving large vessels accept the concept of no passing zones.

(10) Q. How much of an error can you tolerate in misjudging the start of a turn and still make it without emergency maneuvering?

A. The question was answered infrequently on the questionnaires. Casual opinions seem to indicate that a misjudgment of more than half a ship length portends trouble — misjudgment by a ship length means you are already in trouble.

(11) Q. What do you consider emergency maneuvering?

A. Emergency maneuvering for anything but VLCC's is considered to be large speed and helm changes in short period of time. For VLCC's the helm is the only thing that can be effective because they have very little control over stopping distance. Emergency maneuvering usually entails maximum rudder, maximum engine RPM, and/or a change in engine direction.

(12) Q. When making a bend, do you make it as one continuous turn, a series of straight lines, or a group of connected arcs of circles?

A. Most mariners make a bend as one continuous turn rather than a series of straight lines. This depends on the size of the bend and also the currents in the bend. Many times the ship is put on a single heading, knowing that the current will take it

around the bend and essentially results in the desired circular track.

(13) Q. When a course change is necessary, will you normally

a. Change course with a rudder command, and then adjust the rudder angle to steady up on a heading based on the vessel alignment with the new channel?

b. Change course with a heading change command (i.e., come right to 350°) and then adjust to the new channel aid alignment?

c. Change course to a new compass heading?

A. In making a course change to go around the bend, most mariners will initiate the change with a rudder command, adjust the rudder angle as necessary, and finally steady up on a heading based on the vessel's alignment on a new channel.

(14) Q. Does the answer to (13) above depend on the amount of bend? If so, what is the transition?

A. Included in (13).

(15) Q. When making a bend, are you more concerned with your position along the vessel track or with respect to the channel bank? How do you estimate to determine what corrective measures are necessary if you feel that you are out of position?

A. When making a turn, vessels are more likely to be concerned with their aspect to the channel bank than their distance along the turn.

(16) Q. Do you rely more on aids outside the bend or on the inside?

A. Very heavy reliance is placed on an inside initiation aid, with emphasis also placed on the outside of the turn to give them turning rate information. In Europe, the answers differed slightly; the emphasis is placed on your own side of the channel; that is, if you are making a turn to the left and you are upbound, and you are on the right of the channel, the aids on the right side become more important than the aids on the left side. This does not seem to be the same consensus of opinion

among American mariners who would prefer to have emphasis placed such that the turn initiator is on the inside of the turn. Once past the turn initiator buoy, some additional aids are required to determine turn rates.

B.1.3 Open Water Areas, Entrances

(1) Q. When entering the harbor or any restriction following a relatively open body of water:

a. What is the initial contact made for approach?

b. Do you use any non-aid information for alignment?

c. Do you fix the ship's position in any way other than mentally? By what methods?

d. Do you refer to a chart? For what purposes?

A. Initial contact made for the approach is generally the light ship, offshore tower, or large navigational buoy marking the entrance to the harbor. This frequently is after the vessel has emerged from any traffic separation zone. Other landmarks are used to guide them to this reference point, such as offshore light structures, lighthouses and any other points of land that can be picked up on the radar. Generally, chart plotting is done right up to the light vessel. All methods available to the mariner are used, from satellite navigation to DF bearings. In Europe, DECCA is frequently used up to the entrance of the port, and masters of all vessels mark their final at-sea position on a chart for record purposes.

(2) Q. When entering a restriction:

a. Do you feel that an entrance buoy or marker is necessary?

b. If so, how far from the start should it be located?

c. If there is a no entrance mark, how far from the start do you want the ship aligned? What is your minimum distance?

d. What is your point of aim?

e. What is your intended track? Centerline, etc.?

f. How does traffic affect your entrance movements and intended track?

A. An entrance buoy is felt to be necessary for the larger vessels. VLCC's, in particular, feel this to be desirable. VLCC's feel the aid should be located one to two miles just outside the pilot grounds. If there is no fairway buoy, ships still want to be aligned with the channel at least one mile outside the channel entrance for 80,000 ton vessels and two miles for VLCC's. They generally steer by compass until their point of aim has been directed by the fairway buoy, and then they will use the visual alignment of aids in the channel with their intended track, keeping slightly to the right of the centerline of the channel. For narrower channels, most mariners will wait until traffic is clear before commencing an approach.

(3) Q. What are the vessel conditions when entering a restriction?

a. Speed. Maximum, average, minimum?

b. Rudder angles. Standard, maximum?

c. Wind and current effects and your method of compensation?

d. Limiting conditions which dictate not entering the area, other than draft?

A. No specific answers were available for a. through c. In general, fog does not limit transits. In New York, due to the extreme current changes, pilots will not enter Sandy Hook Channel unless the visibility is better than one half mile. For all other areas of the interviews, including Europe, vessels still would enter the harbor under zero visibility provided the majority of their equipment was working properly, particularly the radar.

(4) Q. What differences in your navigation process would you consider when entering an unfamiliar harbor?

A. Not answered, since pilots would be used.

(5) Q. Given a pair of buoys or a bridge through which you wish to pass, how would you maneuver to accomplish this, i.e., what information would you extract from their location without the use of a compass?

A. If the vessel did not have a compass, they must have some marks beyond the gate to give an approach

angle. This would include any other aids ahead, such as lead buoys, ranges or a group of aids on one side of the channel.

(6) Q. Would you do the same thing if you had a compass? No chart?

A. If they have a compass, they are not necessarily as concerned when entering a gate. Mariners will use the compass to align their vessel's position with the gate. However, most prefer to see all aids beyond the gate. Frequently, a radar check will be made to ascertain ship alignment and aid positions ahead.

(7) Q. When navigating in relatively open water, do you consciously attempt to maintain a predetermined track line or do you adjust in the direction of your destination only? What information do you get from an aid system to make decisions on how you maneuver in these situations?

A. In open water, most of the large vessels plan to keep on an intended track. Most of the smaller vessels, such as tugs and coastal tankers, keep going in the general direction of the destination as long as obstructions can be safely cleared.

(8) Q. When there is a marked and unmarked obstruction in your path which is in relatively open water, how do you proceed in order to avoid it?

A. Obstruction avoidance is usually done by radar or by clearing the bearing, i.e., bearing rate is correct. If it's not marked, but the position is known, they usually plan a track around it and ensure that plotted positions keep them well clear of the area.

B.1.4 Aid Information

(1) Q. If there were only fixed aids in your area, could you safely proceed to dock? How would you do it?

A. Most mariners indicated that with fixed aids only it would be very difficult to proceed into the dock. In certain parts of the country, complete elimination of the aids by ice has actually closed the channel. In other places, lack of aids required

that the vessel's draft be reduced before they could move into the harbor. Others indicated that some shore beacons are just as prone to destruction as the buoys. However, most mariners still prefer to see the necessary floating aids in position, and if some of them are out, at least backed up by additional shore aids.

(2) Q. If there were no shore aids, could you proceed by buoys alone?

A. If there were no shore aids, mariners feel they could proceed by buoys alone. There would be more checks required on the off-station characteristics of certain aids. Vessels can and have proceeded under many conditions with only buoys.

(3) Q. Do you use any aids outside of the channels other than ranges? If yes, how and for what purpose?

A. Every master and each pilot has his own shore aids that he uses: "the red barn with the white trim or the steeple on the church." Many such landmarks have been used for years by the pilots. The most frequently cited during our interview process is the Broadway Range, at the New York Battery. This is the only street that runs the full length of Manhattan and appears as a tunnel; a perfect guiding range. Chrysler Tower is another example of a range aid that is used. In the ice navigation season, there are many cases where shore configurations are the only aids available for the pilots.

(4) Q. Where do you prefer to have an aid placed with respect to the edge of a dredged channel?

A. Everyone preferred to have the aids marking the bottom of the dredged channel. They do not prefer to have them up on the bank, because they often get confused as to exactly where the bend of the bank is referenced to the project depth. In Europe, this is not always possible because of high tidal fluctuations along with soft river bottoms.

(5) Q. How do you identify an aid? Colors, shape, location, number, light characteristics?

A. Identification of an aid is generally by its location during the daytime, and by its light characteristic at night. Colors, shape, number have far less meaning to the mariner. Numbers are used primarily to

give references to other vessels as to their location such that passings can be arranged. Buoy number, in essence, designates location. Light characteristics are important for certain aids such as the interrupted quick flashing and the Morse Code A. Many mariners make no attempt to differentiate between the two and a half second flash and a four second flash.

(6) Q. At what distance do you pick up aids in good day visibility? Night? Fog (radar)?

A. The distance at which aids may be detected in good visibility could not be quantified. Mariners said it all depends on the visibility, location of the vessel, height of the bridge, what the background conditions are, etc. Under radar, again, no firm answers could be given because of the interrelationship of radar targets size to sea clutter. The ability to detect an aid is governed by background in the case of visual observations, and the presence of other boats and vessels in the case of radar observations.

(7) Q. When and how do you estimate range and/or bearing from a single aid?

A. In a harbor, this measurement is not generally used except for turns, or as a steering guide. When in the visual mode, learned behavior is the estimation process employed. If necessary, as a more precise measurement, radar observations will be used.

(8) Q. Do you think that there should be a distinct aid identification for a junction? Bifurcation?

A. All mariners felt there should be a distinct identification characteristic for a junction. No U.S. Mariner interviewed knew the meaning of a bifurcation.

(9) Q. What information do you get from unlighted aids at night? How do you get it?

a. In a channel with alternate lighted and unlighted buoys?

b. In open water areas?

A. Unlighted aids are generally considered to be a hazard in the main shipping channels, particularly if there are alternately lighted and unlighted

buoys. In open water areas, unlighted aids are considered to be a hazard unless they are very radar conspicuous. In intermediate channels, where navigation is frequently done by tugs and smaller craft equipped with search lights, unlighted aids seem to serve their purpose. In certain areas of the country where ice conditions occur, unlighted buoys remain on station slightly longer than lighted aids and hence do provide some additional information because of their radar conspicuity. If an unlighted aid is used in an open waterway, mariners feel they must be radar reflective so that the larger vessels can avoid them.

(10) Q. Of what significance to your operations are long range (10 miles) fixed shore lights such as Sandy Hook light?

A. Long-range lights inside of harbors are very seldom used except as a steering aid or as a range. Many of them considered all around lights of high intensity in harbors to be hazards, because they are blinding as vessels pass close abeam. Most mariners feel that more attention should be paid to sectoring, particularly red sectors, but in general feel that higher directional intensity along a channel would be beneficial.

(11) Q. Do you rely on aid information from a bow lookout in poor visibility? Do you routinely report or only upon request? Good visibility?

A. Reliability of the bow lookout is seriously questioned. In fog navigation, many pilots routinely request that a mate be the bow lookout rather than the seaman.

(12) Q. Do you use uncharted landmarks? What would they be? Why are they needed? How do they compensate for deficiencies in the aids to navigation system?

A. Uncharted landmarks are definitely used as aids to navigation and may compensate for deficiencies in aid system, particularly during ice season when the aids are destroyed.

(13) Q. Under normal daylight conditions, could you give an estimate of the differences between the time you sight a buoy, can positively identify it by color, markings, number, assuming equal height above water? Does the color or shape seem to make a difference?

A. Not answered. For most mariners, detection and recognition are not differentiated. They usually state, "Well, I just know what it is because it is there."

(14) Q. Does the availability of radar cause you to depend less on the audio characteristics of aids? What form or audio signal is the most valuable to you? How do you use the information?

A. The availability of radar has obviated the need for sound signals on aids for major commercial vessels. Audio signals are considered to be archaic. The only possible use for them is for small vessels who do not have radar.

(15) Q. Do you depend upon audio signals in good visibility? Night?

A. Same answer as number (14).

(16) Q. How do you estimate when an aid or group of aids is off station?

A. Buoys off station are generally checked before the vessel enters the areas where the aid is going to be used. Mariners usually check them by radar against any other nearby object and visually against the remainder of the aids in the area. Many small craft will not be aware of small deviations of floating aids from the normally assigned position. But, in general, these small deviations would not affect the smaller vessels.

B.1.5 Vessel Equipment

(1) Q. Have or would you ever refuse to bring a ship into port because of inoperative navigation equipment? What equipment and conditions?

A. Most ports have regulations which prohibit the entry of a ship unless the ship is sound and critical equipment in good working order.

Some masters or pilots have said that they would not enter a channel without radar. Others have indicated that they would bring the vessel in any conditions of visibility, but would be more concerned with wind

and current. VLCC's never attempt to enter port without radar.

(2) Q. Would you navigate a vessel in your area if the gyrocompass were inoperative but with a magnetic compass?

a. With a recent deviation card?

b. Without?

c. In reduced visibility?

A. A gyrocompass is not a necessity to navigate in the harbor. Vessels can navigate using the magnetic compass. Both are used in course setting. The magnetic compass with the outdated deviation card is considered a valid heading reference.

(3) Q. Do you use the ship's pelorus when in the harbor? For what?

A. Pilots never use pelorus in a harbor.

(4) Q. When you navigate by radar, do you feel that you need more or fewer aids? Why?

A. When navigating by radar, Europeans felt that they could navigate much better with fewer aids than with more. However, they want them to be at key points and all very conspicuous. The fewer aids, the less chance of confused identities. In the United States, the feelings were not the same. Mariners felt that they didn't need all of the visual aids, but did not want specifically to remove aids just to put in key aids for radar navigation.

(5) Q. How do you verify gyro error?

A. The verification of gyro errors is generally done on a known channel course or on a range.

(6) Q. Do you use the depth finder? When?

A. Depth finders are not frequently used. VLCC's, however, always use their depth finders in confined pilot waters. Pilots sometimes use it when they are navigating into areas where known silting has occurred.

(7) Q. Is there any other equipment you use? Speed log?

A. Speed log is used sometimes by very large vessels but not to any great extent. Speed is more frequently known by engine RPM and telegraph position.

B.1.6 Day, Night, Fog, General

(1) Q. CG reports cite visibility in terms of 10 miles a certain percent of the time. Do you use this information?

A. The context of 10 miles or greater visibility is considered meaningless. Most mariners will indicate that at 2 miles they begin to think about visibility problems, 3½ miles is considered generally good visibility, one mile is considered to be poor visibility, and ½ mile is considered to be very poor visibility.

(2) Q. Do you use radar in clear weather? Why? How?

A. Radar is in constant operation when the visibility is below two miles. The larger the vessel, the more frequently the radar is in use. It is not a question of saying, "When can I turn it on?" but, "When can I afford to turn it off?"

(3) Q. Under what visibility conditions do you shift to radar only?

A. There was no clear distinction of when the shift to a radar alone takes place. Most people know that they shift to radar exclusively when visibility is less than ¼ mile, but whether or not this shift takes place at longer ranges depends on the channel configuration and the number of aids which they can see.

(4) Q. Under poor visibility conditions do you use any electronic systems besides radar?

A. Under poor visibility conditions the Europeans will frequently use DECCA as a backup, keeping it running for a navigational record, tracking them into the area. In the United States there are no other electronic systems that give this type of backup.

(5) Q. How do you estimate visibility conditions in day? Night?

A. Visibility conditions are estimated by comparing what can be seen visually versus the radar indications. Visibility comparisons for day and night are made differently in that a light on a buoy can probably be seen at a greater distance at night than the buoy can be seen during the day in the same absolute measurement of visibility.

B.1.7 Navigational Problems, Electronics

(1) Q. What do you consider the most difficult section to transit in terms of uncertainty of vessel position? Would additional aids improve the situation? How? What accidents have happened in this area?

A. Certain areas were considered particularly difficult because of currents and bends. Sandy Hook was mentioned as a specific area where the currents are very difficult. Making a turn from a down-bound transit in the Delaware Bay to the C&D Canal entrance can be a difficult situation which can become critical during a heavy ebb tide. There seems no question but what turns under adverse current conditions constitute the most critical situation.

(2) Q. What is the section in which you are the most comfortable? Is this due to the particular aid situation? Could the configuration be simplified or the number of aids reduced?

A. No specific answers other than the obvious ones regarding the least traffic and widest channels.

(3) Q. What is your feeling with regard to electronic aids (other than radar or RDF) in harbor applications? Under what circumstances do you believe that you would accept the replacement or reduction of audio-visual aids in favor of an electronic system?

A. In the United States, many of the pilots feel that they would be happy to accept an electronic system if it would help them along their passage. They would not accept it as a replacement for visual aids. They feel there are too many things that could go wrong with electronic systems, and would prefer to

maintain the existing system as a complete backup for any electronic system. In Europe, they are using electronic systems exclusively in several ports.

(4) Q. If a particular channel were made one way, would the channel markings be capable of reduction or simplification? How? Would the situation change your opinion?

A. A one-way channel frequently simplifies the passage in that channel but adds complications as the channels rejoin. This makes intermixing of traffic more difficult, and could cause more problems than it solves. Mariners feel that it is sometimes better to have auxiliary channels than it is to have two-way traffic. However, there always comes the point of a cross-over where intermixing occurs and this can cause confusion.

(5) Q. Is there any particular type of channel or harbor element which seems more critical in terms of navigation accuracy? i.e., marking junctions, turning points, entrance points versus a long straight channel? Why?

A. Most critical channel harbor element is the bend, regardless of how it is configured, either as a junction, a turning point or entrance.

(6) Q. Is there any section where the abundance of aids can possibly result in confusion in identification, particularly for someone who is unfamiliar with the harbor? Where? Why? Which aids should be removed to reduce the confusion?

A. An abundance of aids can definitely cause confusion and lead to misidentification. Hopefully, the solution is to thin out the aids. Where this is not possible, there should be better distinction in identification of the aids. This is particularly true at night.

(7) Q. Is there a requirement for aids where none currently exists? Why? What information is missing from the current system?

A. Answered more specifically under the individual harbor comments (see Section B.2).

(8) Q. Are there any areas where bank suction is a significant problem? Any areas where it becomes helpful?

A. There are many areas where bank suction is a problem, but also there are the same areas where it's helpful; for example, in the very tight, narrow, winding channels in New York in the Arthur Kill area. In areas such as Galveston which has very narrow channels, bank suction can become a significant problem because the current does not seem to be too detrimental to the overall process of navigation as long as the channel is reasonably straight. At bends, bank suction becomes a more signifcant problem and tends to cause people to shear to the wrong side of the bank.

(9) Q. Are there any areas where tug assistance is required other than docking? Why?

A. Yes, there are areas where tug assistance is required. These are areas that are considered to be extremely hazardous and continuous docking type maneuvering is the method of navigation rather than piloting.

(10) Q. Where optional routes exist, what governs your choice?

A. Very infrequently are there optional routes. Kill Van Kull and the Arthur Kill is one area where optional routes do exist, but it is only the difference between an in-bound and an outbound transit since the vessel cannot turn around once in the waterway.

(11) Q. Have you ever found yourself in the position of having misidentified an aid? What could be done to prevent this?

A. A few masters indicated that they did misidentify an aid. They felt it was entirely their own fault. One of them indicated that he misidentified an aid in flat calm because of the glare of the sun.

(12) Q. What situation do you think creates the greatest potential for going aground?

a. Misidentification of aids?

b. Failure to properly use aids?

c. Misjudging the effects of wind or current?

d. Misjudgment of vessel maneuvering characteristics?

e. Meeting and overtaking situations?

A. The greatest potential for going aground was identified in Europe as misidentification of aids. This was not the case in the United States. In the U.S., misjudgment of the wind and current effects was considered by the pilots to be the biggest problem. (This coincidently agrees with the results of accident data.) Passing situations under adverse wind or current were considered a major problem in narrow channels.

(13) Q. When navigating in your area by radar, with essentially zero visibility, do you:

a. Actually measure radar lines of position from fixed or floating aids and fix the ship's position on a chart or some other formal fashion?

b. Estimate the ship's position and desirable course of action based on a comparison of the ship's head with the "radar picture"?

A. The use of radar in a harbor consists essentially of estimating ship's position and course of action based on a comparison of ship's head with the radar picture. Seldom is plotting ever done; however, the cursers and range rings are used to give better estimation of ranges and bearings. They do use prominent landmarks, if necessary, for the answer to Question (14). In many cases in ice, there are only prominent landmarks remaining for vessel use.

(14) Q. Under the conditions of (13) above, do you use prominent landmarks that are not classified as aids to navigation? Except in a marked channel, would you have more confidence in a decision based on radar presentation of aids to navigation or based on the presentation relative to the ship's position of known landmarks?

A. Included in (13).

(15) Q. Do you use Radio Beacons in your area?

a. In clear weather?

b. In low visibility?

A. Radio beacons are used up to the entrance of the harbor, very seldom if ever used within a harbor. The only exception was mentioned by one pilot who stated he used a radio beacon when all the buoys were out during the ice, but found it rather unsatisfactory in terms of precision.

(16) Q. If so, do you actually plot the information? If the bearings are not plotted on a chart, how do you use them?

A. When DF bearings are taken, they are nearly always plotted. The only time they are not plotted is when they are used in a "homing" mode.

B.2 SPECIFIC PORT COMMENTS

These comments were received from mariners during the course of expert interviews. In many cases, they represent only the opinion of a single person.

B.2.1 Baltimore and Annapolis

(1) Swan Point Channel is not used. It was marked when there was an intention to dredge the C&D Canal to 45 feet. This was never accomplished, so Swan Point aids are not required for channel definition, hence all but one lighted aid can be removed.

(2) The cans 15c and 17c at the Craghill Angle are unlighted and therefore do not add any information at night. The same essentially applies to all of the unlighted aids in the area from the C&D Canal to the Bay Bridge. Over 70 percent of the movements occur at night (pilot's estimate).

(3) The South River Entrance buoy, nun "2," is not useful to boatmen, and is considered a hazard at night. The same applies to can "75" near Thomas Point Light.

(4) The red sector, removed from Bloody Point light, should be replaced in the opinion of both pilots and boatmen.

B.2.2 New York

(1) Old Orchard Shoal light is not used and could be reduced to a secondary aid marking an obstruction.

(2) Lighted buoy "1" North of Point Comfort does not seem to have any utility. The same applies to the Boundary Light

Beacon South at Red Bank. This could be more effective if added to the Raritan Channel.

(3) Synchronized flashing of the reds, greens, and whites at Ward Point would help eliminate the confusion of many aids in one area.

(4) Romer Shoal light is only used as a steering aid for Swash Channel. Its intensity could be reduced and sectored coverage added.

(5) The RB C between Old Orchard Shoal and Chapel Hill South Channel is not used.

(6) Coney Island light can be reduced to a 4 or 5 mile light.

(7) Gravesend Bay anchorage should have its inner limits marked with a range, or set of lighted anchorage markers.

(8) Constable Hook Range is too far South.

(9) Several of the aids around Robbins Reef can be removed, including the can nearest Robbins Reef light and FLR beacon to the NNE of the light. A lighted aid should be added to the south of the light to mark the north exit boundary from Constable Hook.

(10) C "1" should be located further East in Constable Hook Range, and lighted.

(11) N "10" near the Bayonne Bridge could be removed. It is too close to the bridge to be useful.

(12) The lighting of N "24A" and FL R 4 sec "4" at Bergen Point should be reversed. This would provide better turning guidance information.

(13) C "3A" should be removed and C "3" relocated to the inside of the Hook in Newark Bay Reach. "3A" is a hazard to tug screws when assisting outbound vessels.

(14) N "4B" to the North of the lift (RR) bridge could be removed as it is too close to the bridge to provide useful information.

(15) The lighting of C "7" and R "2" at Newark Bay South Reach should be reversed.

B.2.3 New York-Long Island Sound

(1) Replacement of the unlighted bell buoy "23" at Prospect Point by a lighted aid has been requested several times by the pilots.

(2) A lighted aid in place of the unlighted aid South of Valiant Rock has also been requested. This aid was lighted some time in the past, and a return to its original status has been recommended.

B.2.4 Delaware Bay

(1) The pilots indicate that the sea approach buoys for the traffic separation zone are unsatisfactory to masters. The radio beacons are inoperative a high percentage of the time. RACONS should be placed on each of these two aids, both to alleviate the radiobeacon problem and to identify the buoys from the large number of fishing boats which congregate around them.

(2) The pilots do not like gated pair buoys. The channel is actually wider than the project boundaries in most of the Bay. Under these conditions, it is easy to arrange passing so that a lighter draft vessel can exceed the project boundaries. If gated pairs are used, the traffic will funnel through them, creating problems. In the lower ends of the bay, vessels are proceeding at nearly sea speed (about 16 knots), and funneling will cause traffic delays. In addition, the funneling will cause all other types of traffic to be in the main ship channel.

(3) To preclude the last portion of Item (2), secondary marked channels are recommended by the pilots, and apparently endorsed by the towboat associations. There have been several ideas for the location of these channels, but no firm proposals to date.

(4) The Coast Guard has indicated that they are having mechanical difficulties in maintaining the electric generators at Brandywine Shoal and Miah Maull Shoal. There is a possibility of converting to batteries with a significant reduction in candlepower. This appears to the pilots as a great sacrifice in safety, as these are primary aids. There may be some significance to highly focusing the light at a large reduction in power

consumption but with no loss in intensity for the navigation of the channels.

(5) Additional lighted aids are suggested at the following Loran-C coordinates:

a. 9930 Y 52198, Z 70073, to give rate of turn information on a downbound transit.

b. Y 52165, Z 70002.5 and Y 52159, Z 69987.

(6) N "34" and "38" on the Liston Range could be eliminated.

(7) An aid is needed to mark the Northern end of the Liston Range Anchorage.

(8) An aid is considered desirable to mark the 9 foot shoal on the cut across the flats from Liston Range to Cape May, Y 52162, Z 70070.

(9) Sound signals are not necessary on primary channels but would be useful on secondary channels.

(10) The purpose of, or location of N "10L" at the Northern end of Liston Range, is questioned.

(11) A channel truncation or cutoff definition of the Liston, Baker Range junctions is desired, since there is available water on the inside of this bend, with both ends marked by a lighted aid.

(12) There is confusion in the red lights between the Reedy Island Dike Beacons and the front light of Baker Range.

(13) The truncation of the Reedy Island – New Castle Range junction should be marked by lighted aids at each end rather than one aid in the middle of the cut.

(14) Buoy "1D" at the entrance of Deepwater Port Range should be relocated, either opposite R "4B" or to the outside channel boundary junctions of the Bulkhead Bar and Deepwater Point Ranges.

(15) Unlighted aids in the river are more significant than some of the unlighted aids in the bay. Low visibility requires the use of radar more frequently, and the unlighted aids provide good radar information.

(16) During the past decade, industrialization and urbanization have resulted in many ranges being obscured by mercury and sodium vapor lights. The intensity of the range lights has not changed. This causes extreme difficulty in locating the range lights, particularly with the addition of red colors in commercial advertising. This is causing difficulty for licensed masters who may enter the port not more than 7 or 8 times a year.

APPENDIX C
INFORMATION AVAILABLE FROM AIDS

This appendix presents the method of development and use of parameters describing information obtained from aids to navigation. It is divided into three sections as follows:

Section C.1 – Section C.1 presents basic definitions regarding information available from single aids, and develops a method of defining coverage and accuracy for visual aids to navigation which is analogous to that used for radio navigation systems.

Section C.2 – Section C.2 discusses the use of visual aids to navigation in a basic "building block" concept. The information available from these basic configurations can be used to synthesize integrated harbor aid to navigation systems.

Section C.3 – Section C.3 presents illustrative examples of the use of the basic configurations of Section C.2. A number of harbor elements are synthesized, and the use of the information in arriving at a "state estimation" by the navigator under a variety of conditions is presented.

A listing of notation and definitions is presented in Table C.1.

C.1 DEFINITIONS AND COVERAGE ANALYSIS

C.1.1 Information Available from a Single Aid

A single aid to navigation can be considered a reference point in one of the following two reference frames:

(1) Geographical Reference Frame. An example of such an aid is an offshore light structure or major shore lighthouse giving notice of landfall in a particular geographic area. These types of aids in general have no lateral significance.

(2) Local Reference Frame. The position of the aid is determined by the need to provide a message which can

Table C.1
Notations and Definitions

Distances:		
D_R	=	distance to red boundary, measured perpendicular to the boundary
D_B	=	distance to black boundary, perpendicular to boundary
D_{RC}	=	distance to the closest red aid
D_{BC}	=	distance to the closest black aid
D_{RS}	=	distance to the second closest red aid
D_{BS}	=	distance to the second closest black aid
S	=	aid spacing for symmetrically placed aids
S_A	=	aid spacing for auxiliary aids
S_O	=	aid spacing on the outside of a bend
So/N	=	aid spacing based upon an increased number of aids on the outside of a bend
SI	=	aid spacing on the inside of a bend
SI/N	=	aid spacing on the inside of a bend based upon the number of aids
D_T	=	distance from the vessel to the termination of the harbor module
Angles		
γ	=	angle between ship's heading and actual track over the ground, i.e., crab angle
B	=	angle of the channel bend
R	=	rudder angle
θ_R	=	angle between the nearest red aid and the perpendicular to the channel boundary
θ_B	=	same as θ_R but to the black side
Ψ_{RC}	=	angle between ship's head and the closest red aid
Ψ_{BC}	=	same as above, but to the black side
Ψ_{RS}	=	angle between ship's head and second closest red aid
Ψ_{BS}	=	same as above, but to the black side
ϕ	=	angle between ship's position and an aid or aid combination on the channel centerline or extension of the channel centerline. Ex. ϕ_{7-8} = angle to the centerline at aid pairs 7 and 8; ϕ_8 = angle to aid 8 located on channel centerline extension.
ϕ_c	=	angle to closest aid on the centerline. Ex. ϕ_c = angle to front range marker
ϕ_s	=	angle to second closest aid on the centerline. Ex. ϕ_s = angle to near range marker
θ_{BS}	=	$\theta_{even\ \#}$ = angle from next black aid to vessel, listed by number
θ_{RS}	=	$\theta_{odd\ \#}$ = angle from next red aid to vessel, listed by aid number

be understood without the need for a specific geographic reference frame. These aids normally have lateral significance; the criticality of the lateral position varying with the particular use of the aid. In most cases the reference frame is the position of surrounding or adjacent aids.

Intrinsically, an aid to navigation possesses two characteristics:

(1) Position

(2) Message

All information available to the mariner lies in these characteristics. If the information is to be of value, the basic criteria are that the aid must be:

(1) Within Visible Range (or Radar)

(2) Identifiable (i.e., not mistaken for another aid)

(3) Readable (i.e., its message must be available)

Given that the aid can be identified and read, the following four classes of information can be obtained:

(1) Line of Position – Measured or estimated

(2) Position – Combination of range and bearing (measured or estimated)

(3) Preferred Track Line

(4) Action Recommended

The basic operational characteristic of any aid is its range of usefulness, i.e., that range at which the aid may be properly identified and read. For a single aid, the quantifiable characteristic may be called "coverage."

The problem in quantifying coverage for purposes of modeling an aid to navigation lies in the parameters assigned to the

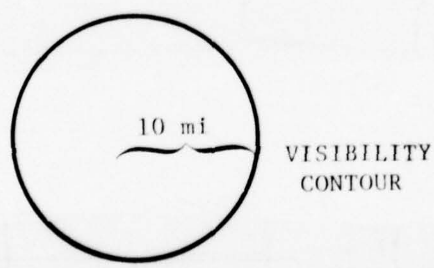
limiting coverage contour. The following are considered the basic possibilities for coverage criteria:

(1) Range of Visibility, or radar range

(2) Accuracy: A subset of the basic Visibility Contour for an aid to navigation would be the "Accuracy Contour." In order to assign the parameters associated with accuracy, the use of the aid in the process of navigation becomes involved, as do the process methods, particularly in terms of measurement method. From the point of view of information available, if the aid can be seen, it can be used as an information source.

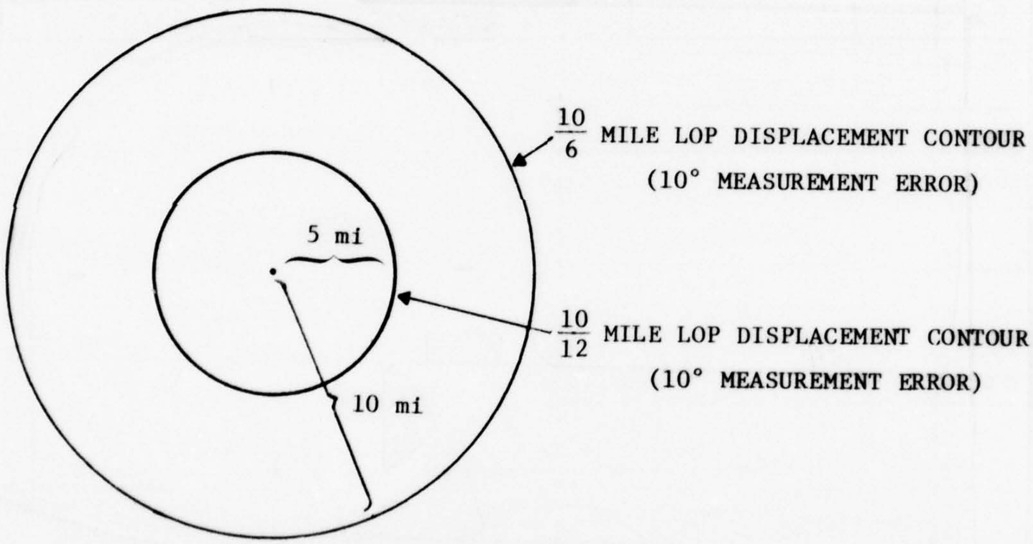
Whether the quality of that information source is sufficient to meet the "Requirement" requires an analysis to be made of the "Quality" of the information available. For the first level of information "quality," one can analyze the four classes of available information (listed above) and present the accuracy available for this information in the form of a contour based on the accuracy of the measurement of the information.

As an example, consider an aid to navigation with a nominal range of 10 miles. The visibility coverage diagram would appear as below:



Now let us impose a "quality" parameter in the form of measurement accuracy. We will presume the line of position desired is a bearing, and that the measurement process (regardless of range from the aid) has a fixed error of 10°. Using the "rule

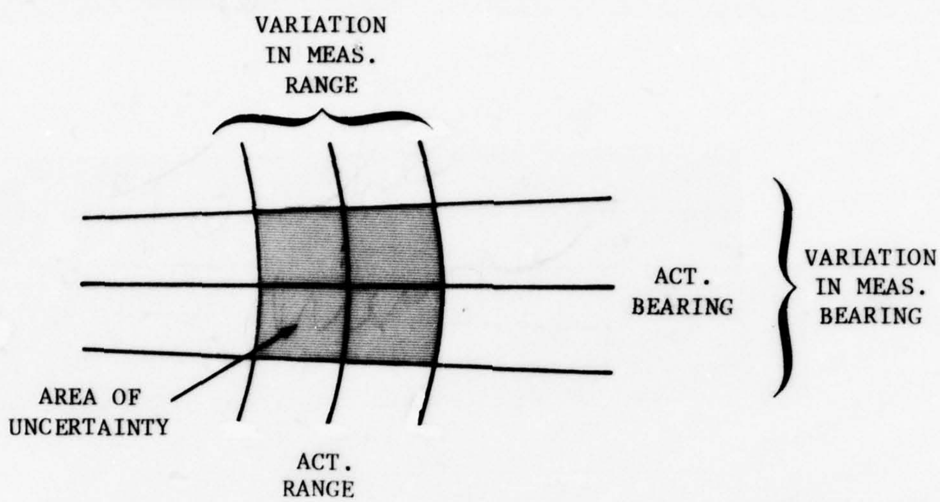
of 60" approximation, (1 mile of error per 60 miles per degree) the measured line of position would be displaced from the actual line of position by 10 miles at a distance of 60 miles from the aid or 10/6 of a mile at the limit of visibility (10 miles). One can now draw a series of accuracy contours (all contained within the basic visibility contour) by plotting areas where the measured line of position will be displaced by a distance NO GREATER than x miles, based on a measurement error (which will usually be described statistically) of y degrees. Using the approximation mentioned above, the radius of the (circular) contours is 60•x/y. Two examples are given below.



The necessary algorithm to determine bearing information available must therefore consider both measurement accuracy and visibility. Similarly, distance measurement accuracy would lead to circular contours of distance accuracy.

For position accuracy, a combination of two LOP displacements would yield the typical position error figure. Fortunately, for a combination of range and bearing information, the lines of

position yielding the fix are everywhere orthogonal and crossing angles do not enter the picture.



C.1.2 Position Fixing Information Available from Multiple Aids

Information available for positioning using multiple aids is essentially identical to that from a single aid except that there are additional combinations of lines of position available. Given the two forms of lines of position, i.e., bearing and distance, a simple configuration of two aids established as reference yield the following information for purposes of position fixing:

(1) Two Bearings

(2) Two Ranges

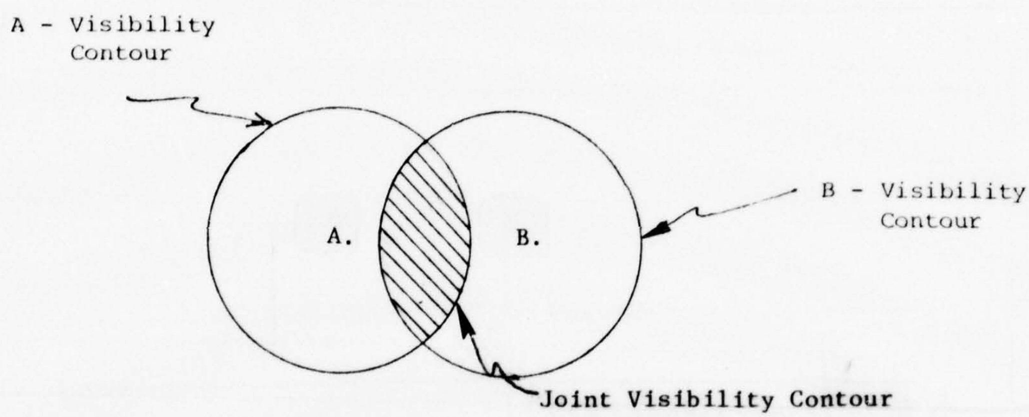
(3) Range to one, bearing to the other

(4) Combinations of the above (multiple fixes)

Of all the positioning methods used, the two-bearing method is the most common and will be used here to illustrate the

technique of generating a fix coverage contour. Obviously, as the number of aids available increases, the number of lines of position increase and the coverage diagram becomes more complicated. The mathematics, however, is readily expandable from the simple two aid condition which will be described here. The basic steps in identifying a fix coverage contour are as follows:

(1) Determination of the Joint Visibility Contour. Consider two aids with visibility coverages of 10 miles each. The joint coverage is obviously that area where the coverage overlaps and represents the absolute limiting contour for use of the aids as a multiple configuration. This is depicted below:



As with a single aid, all information available from two reference point aids may be obtained at any point within the joint coverage.

(2) Determination of Information Quality. A Mariner may fix his position by:

(a) Cross Bearings from A and B

(b) Bearing from A, Range from B (and vice versa)

(c) Range from A, Range from B

(d) Combinations of (a), (b) and (c)

Let us now consider the Quality of the information in terms of the positional accuracy of the measured fix. Three considerations are involved.

(a) Measurement Accuracy

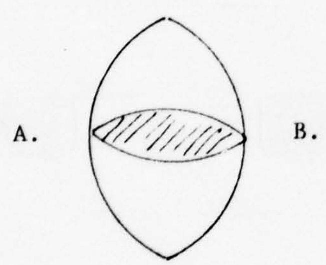
(b) Geometric Dilution of Precision (GDOP)

(c) Angle of Cut (Crossing Angles) of the LOPs

For illustration, consider the fixing method to be cross bearings from A and B. The following assumptions will be made.

- Fixed Measurement Error (10°)
- Limiting Crossing Angle (15°)
- Geometric Dilution of Precision for angular measurements according to the rule of 60 (1 mile per 60 miles per degree).

Considering crossing angle first, the joint coverage contour, given previously, can be constrained as shown below:

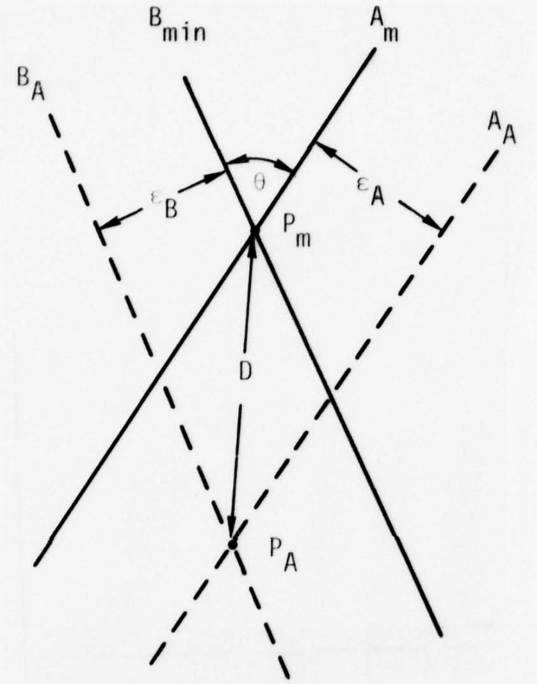


Crosshatched area limited by angle of cut.

Clear area limited by visible range.

Consideration now must be taken of measurement accuracy and the Geometric Dilution of Precision. Ignoring the usual statistical definition of accuracy, let us assume a single set of measurements is taken (bearings) and each bearing is in error by 10°. Further, assume the measurement is taken at a range of 6 miles from the associated station.

By the rule of 60, each measured line of position will be displaced from its actual line of position by 1 mile. (10 miles at 60 miles = 1 mile at 6 miles). For a given crossing angle θ, the situation will appear as follows.



B_A, A_A = Actual LOP's
B_M, A_M = Measured LOP's (in error by 10^o or at this distance by 6 miles)
E_A, E_B = LOP Displacements
P_A = Actual Position
P_M = Measured Position
D = Position Error in Distance
θ = Crossing Angle

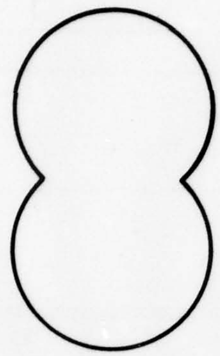
Since E_A & E_B are known, in this case to be 1 mile, the actual length D can be calculated, knowing θ, by the usual trigonometric methods.

In actual practice, a formula can be derived to represent D in statistical terms, given a measurement error E in statistical terms (1σ, 2σ, etc.) for all possible values of θ. Obviously, the error E (in degrees) must be translated in the formula to E in linear units by the use of the Geometric Dilution factor which in the case of bearings is

$$E \text{ miles} = \frac{E \text{ degrees X Distance from station (in miles)}}{60}$$

A contour may then be drawn, for any derived value of D, for any given value of E

A.

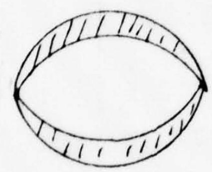


B.

Contour within which D (position error) will not exceed X miles for a measurement error not exceeding Y degrees.

This contour must then be superimposed on the previously derived contour and will yield a final coverage contour.

A.



B.

Based on the limits of visibility of the aids, bearing LOP cross angles (15°), and the Azimuthal Geometric Dilution Factor, the position error within the crosshatched area will not exceed D miles (in statistical terms), for a measurement error of E degrees (in statistical terms).

A like treatment can be accomplished for other line of position types to yield FIX COVERAGE. To simplify the arithmetic, the correlation coefficient is usually considered zero between the two errors, unless information to the contrary is available.

C.2 BASIC NAVAID CONFIGURATIONS

C.2.1 Introduction

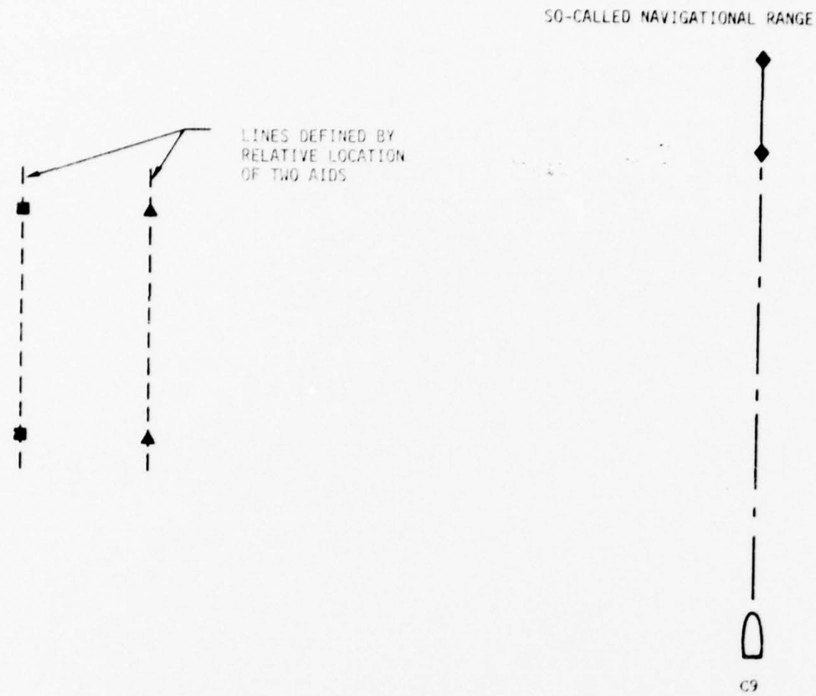
The establishment of a configuration of more than one aid, for use other than formal position fixing by measurement of lines of position, implies the conveyance of a message dependent on the relative position of the aids. Obviously, the use of single aids within a multiple configuration in the process of navigation is possible (i.e., the last buoy on the port hand of a marked channel, even though forming a "gate" with the starboard hand buoy, becomes a single aid when it is considered to mark or "cue" a turn).

The basic assumption underlying the treatment of multiple aids will be the fact that the only possible message that can be conveyed is a STRAIGHT LINE. An indirect message, depending on the navigator's use of the aids, is relative distance. Measurement of actual distance to one or more of the aids reduces to the single aid case. The information from two aids is simply that available from any two fixed points in a reference frame, the straight lines associated with the aids. These lines take two forms, and either can be utilized to extract the information.

(1) The line joining the two aids, and extended beyond each. This is essentially a "range" or leading line and the relative position of two aids defines the direction of this line. These are shown in Figure C.1 (Part A).

(2) A line indirectly available, which makes a desired angle of intersection with the line joining the aids. In the simplest case, this line is perpendicular to the line joining the aids, but this is not always true. Two examples are shown in Figure C.1 (Part B)

Part A. Lines Directly Defined



Part B. Lines Indirectly Defined

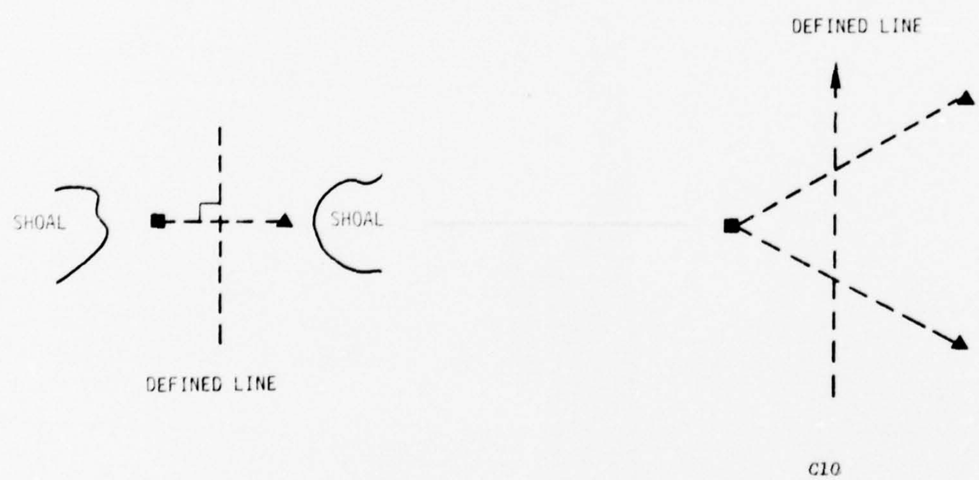
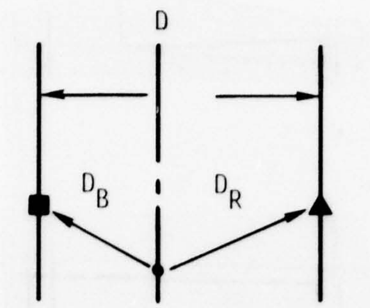


Figure C.1 Lines Defined By the Relative Position of Two Aids

(3) The last bit of information implicit in the relative position of aids is the relative distance (or difference in distance to the aids), as shown below.



In maintaining track (or better yet, estimating position) within a marked channel, the factor (DB-DR) is available. Direct measurement of either DB or DR reduces to the single aid situation.

In summary, multiple aids in the so-called "guidance" configuration present information in the form of a straight line (direction), from which, in some cases, other straight lines can be derived. In the process of navigation, the method and accuracy with which the existing information is measured and used determines accuracy achieved.

C.2.2 Gated Pairs

Consider a straight channel marked with gated pairs of red and black buoys. The line joining buoys of like color is parallel to the channel direction, the line joining each of a pair is perpendicular to the channel direction. Only two pairs will be considered. Additional pairs may serve to refine the data measured but add nothing to the parametric definition of the information available.

The following information is available from the aids:

(1) The channel boundary — useful in the process of navigation as a danger warning.

(2) The direction of desired track — useful in that the mariner will wish to maintain this as closely as possible.

(3) The channel width which, hopefully, but not necessarily, is known.

The position of the aids define the foregoing (within the limits of placement accuracy).

C.2.2.1 Positional Parameters

For purposes of identifying the informational parameters involved, let us assume that, initially, the mariner is located at position A (Figure C.2), on the centerline. We can now define the positional parameters available to him.

(1) CASE A. The angles ϕ_B and ϕ_R are those subtended by marker buoys. This is the most direct information available. When $\phi_B = \phi_R$, he is on the centerline. Similarly;

(a) if $\phi_B > \phi_R \rightarrow$ Right of ℄

(b) if $\phi_B < \phi_R \rightarrow$ Left of ℄

(c) if either ϕ_B or $\phi_R = 0 \rightarrow$ TROUBLE

D_B and D_R are the distances to channel edges. Although $D_B = D_R$ indicates ℄, the ability to estimate this parameter is minimal from this position.

θ_B, θ_R are the angles between nearest gate buoy and nearest point of channel boundary. Also minimal application.

D'_B, D'_R are the distances to first pair. Usefulness increases as distance to center of the gate decreases.

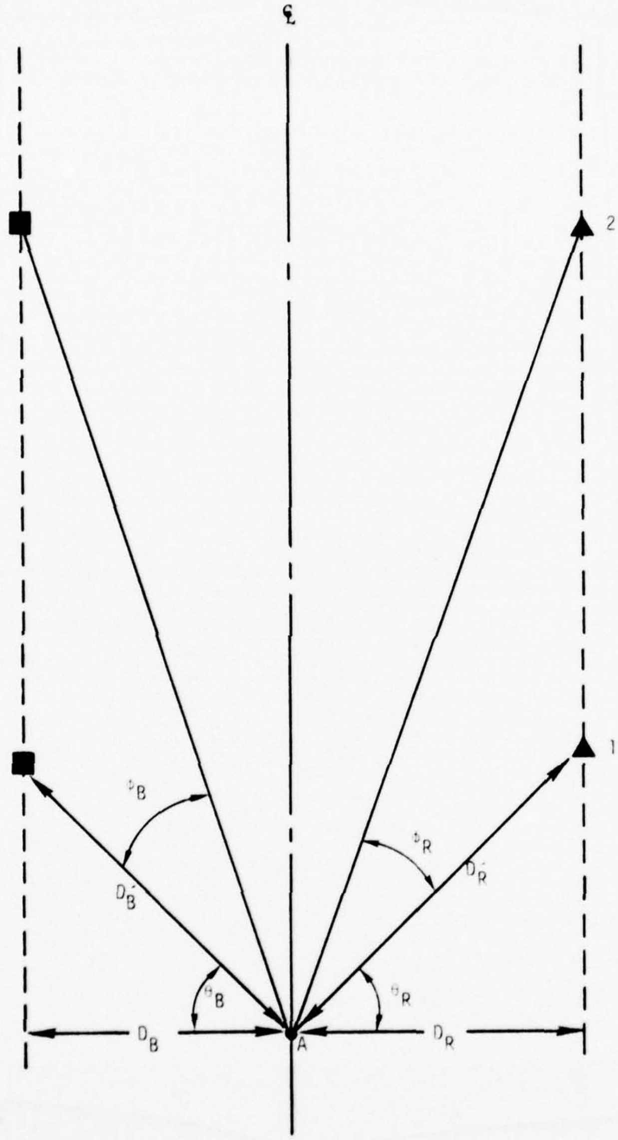


Figure C.2 Position Information Available from a Gated Configuration

(2) CASE B (Figure C.3). The mariner is now positioned exactly with Gate 1. Using the same parametric definitions as before, it can be seen that

$$\phi_B = \theta_B \qquad \phi_R = \theta_R$$
$$D_B = D'_B \qquad D_R = D'_R$$

From the point of view of fixing position relative to centerline, it is obvious that only the following information is available.

(a) The ϕ, θ angles

(b) The D_B, D_R distances

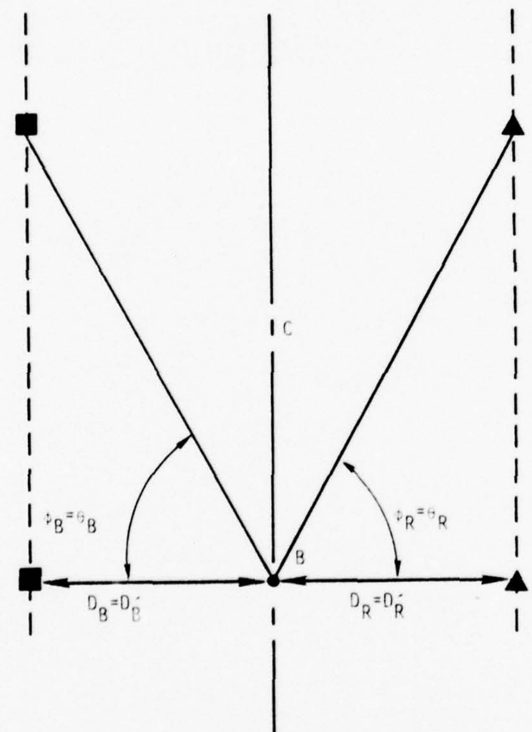


Figure C.3 Position Information Available from a Gated Configuration (In the Gate)

C.2.2.2 Projected Track Information

It is now necessary to expand the foregoing cross track error discussion to include the availability of Decision Making Information (Projected Track Information). This involves the process of navigation wherein vessel heading becomes an input parameter to information available.

Consider the same situation as in Figures C.2 and C.3, but with additional parameters applied by knowledge of ship's head. This information is available in two forms.

(1) Compass Heading

(2) Range (leading line) formed by the position of the observer and a ship's head reference point (Jack staff, mast, etc.).

The terminology, as shown in Figure C.4 (and subsequent figures) is as follows:

ψ_{B2}, ψ_{R2} – Angles between perceived ship's head and the farther of the gate buoys

ψ_{B1}, ψ_{R1} – Angles between perceived ship's head and closer buoys.

An alternative set of angles might be the angle between the perceived channel direction and the ship's head. These parameters, however, involve an additional step in the estimation process.

In order to ultimately assign numbers to the accuracy required and achievable from this configuration, three new parameters will be introduced, two of which are fixed and one of which is variable as the vessel proceeds.

W = Channel Width
S = Buoy Spacing
D = Distance of vessel to nearest buoy pair

It is expected that the relative importance assigned to measurement parameters will vary with D. For example, when D = 0

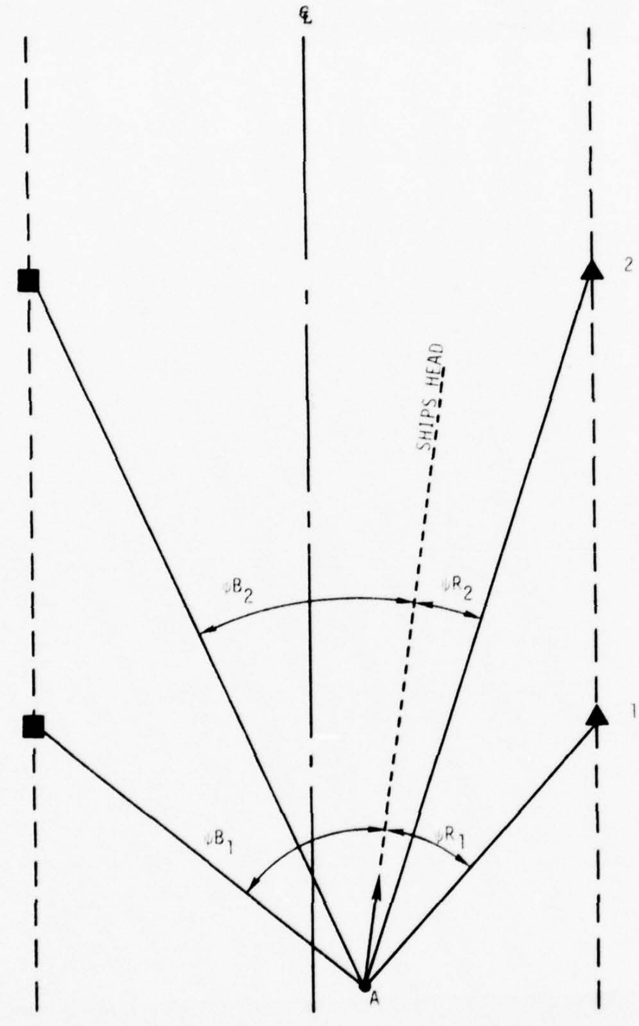


Figure C.4 Angle-Off-the-Bow Observations Available in a Gated Configuration

(vessel is in the gate), the perceived value $(D_B - D_R)$ is probably the best indicator of cross track error. On the other hand, when $D = S/2$ (vessel is between gates, as in Figure C.3), the value $(\phi_B - \phi_R)$ is probably the best indicator of cross track error.

Figures C.5 and C.6 will be used to illustrate the dual process of perception of cross track error from available information and the perception of projected track (or corrective action required).

(1) Position (Cross Track Error) Information (Figure C.5). Measured parameters:

(a) $\phi_B - \phi_R$

Since $\phi_B > \phi_R$ mariner perceives position to the right of track line. The actual distance can be calculated since cross track error, i.e., distance from centerline is an elementary geographic function of ϕ, W, S, and D.

(b) Perception of difference $(D'_B - D'_R)$, the difference in distance to the buoys might be used, and must be considered available information, but estimation process would be inaccurate until the vessel is very close to the gate. The importance of this information varies inversely with D.

(c) $D_B - D_R$ Requires estimate of distance of vessel from the boundary. This is of least importance until D approaches zero. However, the factor $W/_2 - D_R$ represents the cross track error and numerically is the perceived result of the process.

In summary, the mariner perceives that he is off track by the information provided by the estimation $(\phi_B - \phi_R)$. The amount of error (positional) $(W/_2 - D_R)$ is a geometric function of $(\phi_B - \phi_R)$, S, D, and W. S and W are factors determined by the aid configuration.

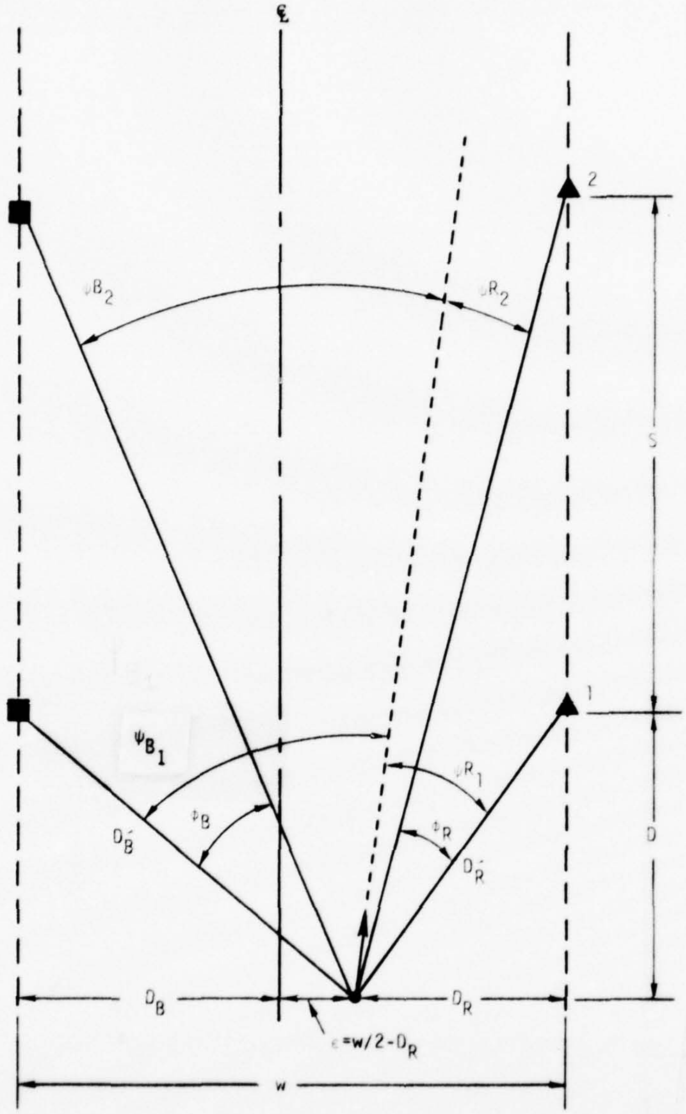


Figure C.5 Position and Guidance Information Available in a Gated Configuration (In Between Gates)

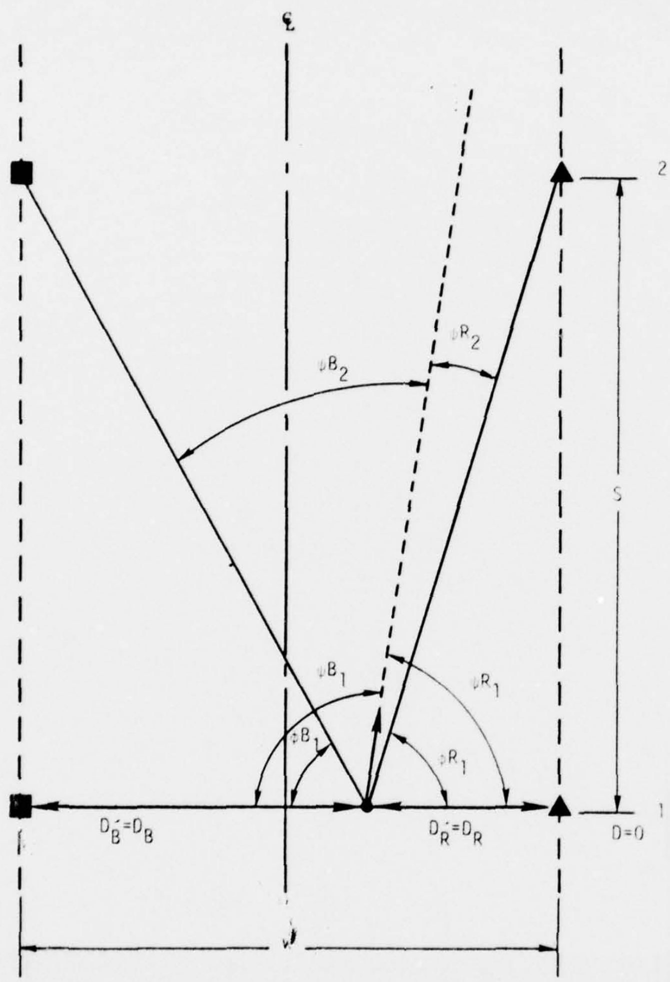


Figure C.6 Position and Guidance Information Available in a Gated Situation (In the Gate)

(2) Projected Track Information (Figure C.5). Measured Parameters:

(a) $\Psi_{B2} - \Psi_{R2}$, $\Psi_{B1} - \Psi_{R1}$

Already knowing from part 1 above that he is to the right of track, the navigator can now estimate his projected track (in the absence of any wind or current effects), by observation of angles

$$(\Psi_{B2} - \Psi_{R2}) \text{ and } (\Psi_{B1}, - \Psi_{R1})$$

It is apparent that he must correct the ship's head in such a manner that Ψ_{B2} decreases and Ψ_{R2} increases. As a minimum action, he would like his corrected heading to be parallel to the channel heading. There appear to be no simple geometrical relationships to allow projection of this track. Therefore, it must be assumed that the mariner will correct his ship's head such that Ψ_{B2} becomes less than Ψ_{R2}. This ensures that he will be steering away from the red boundary and toward the centerline (since, in the case illustrated, his position is to the right of center). If his actual position was to the left of center, it is quite conceivable that Ψ_{B2} would still be greater than Ψ_{R2}.

The positional information derived from the ϕ, θ and D measurements must be included with the Ψ measurements (projected track), to arrive at a heading change decision. The continuous process of such comparisons probably constitutes a minimal definition of the process of navigation in this situation.

It is now possible to examine the changes which take place as the vessel proceeds to a second situation, i.e., his position is directly "in the gate," as shown in Figure C.6. This is, in reality, a special case of the preceding situation, where the distance D has collapsed to zero. The difference, and it is an important difference, is that the priority (importance) of Positional Information parameters has changed to distance (D_B, D_R) rather than angle (ϕ_B, ϕ_R). This is also the most likely point where a heading change might be effected since the absolute accuracy of the cross track error is probably the best.

(1) Cross Track Error (Position). Measured Parameters:

(a) $D_R - D_B$
The results of interviews would seem to indicate this parameter as the most important at this time.

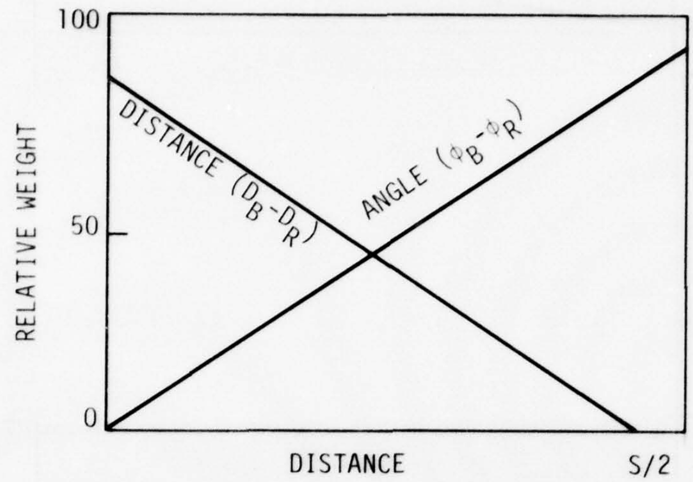
(b) $\phi_B - \phi_R$
The relative values of ϕ_B and ϕ_R are available as information in this case, but are of less value (and probably of less accuracy) for positioning and determination of cross track error.

(2) Projected Track. There is relatively no difference in the information available for projected track with the exception of the fact that the angles Ψ_{B1} and Ψ_{R1} are essentially useless.

C.2.2.3 Parameter Sensitivity

For positioning information, i.e., determination of cross track error, there is a crossover point wherein relative distance to a "gated pair" becomes more accurate and of more use than the angle measurements. This is a function of D, the distance from the measurement position to the gated pair and is, of course, going to cause the time of switchover from one parameter to the other to be a function of the buoy spacing S. When D = 0, the parameters D_B and D_R are more accurate. When D is large, the factors D'_B, D'_R are available but the angles (ϕ) are the error measurement criterion. Of interest is the location of the changeover point.

It is suggested for purposes of the study, that a curve of weights be postulated, for later verification. Such a curve would take the form:



C.2.2.4 Summary of Information Available from a Configuration of Two Gated Pairs of Buoys

(1) Explicit Information Presented:

(a) Straight lines between aids of like color, for use as reference direction, and boundary warning.

(b) Distance between aids in a pair, i.e., Channel Width.

(c) Distance between aids of like color, i.e., aid spacing.

All information available from a single aid is also available from any one aid in a multiple configuration. More than two pairs of gated aids do not change the form of the information available and therefore the treatment for two can be extended with little modification.

(2) Parameters Derivable from Two (or More) Gated Pairs of Aids. For purposes of definition, the term centerline refers to a line, perpendicular to the line joining each aid of a pair and halfway between them.

(a) For Determination of Instantaneous Cross Track Position

ϕ_B, ϕ_R – Angles subtended by buoys as seen at position of observer (Figure C.2)

D_B, D_R – Distances to channel boundaries (lines defined by aid positioning) (Figure C.2)

D'_B, D'_R – Distances to nearest red and black buoys in the gate. D = 0: in the gate (Figure C.2)

θ_B, θ_R – Angles subtended by the nearest buoys and the nearest point on the channel boundary (Figure C.2)

W – Distance between buoys of a pair (Channel Width)

S – Distance between buoys of like color (Buoy Spacing).

(b) For Determination of Projected Track:

Ship's Head – Direction ship is "pointing" as determined by compass head or, more usually, by line extended ahead from observer, through bow of ship, or other on board reference (jack staff, mast, etc.).

Ψ_{B2}, Ψ_{R2} – Angles between ship's head and second pair of B and R buoys in sight (Figure C.4)

Ψ_{B1}, Ψ_{R1} – Angles between ship's head and nearest buoys (Figure C.4)

(3) For Special Use in Determining the Use of the Foregoing in Process of Navigation

D – Distance of vessel from center of gate.

Sensitivity – Weight assigned to the result of the measurement of foregoing parameters, as a function of D

(4) Ship Situations:

(a) Approaching a "gate." Two gates visible ahead.

(b) In the gate. One buoy of first pair abeam to each side, one pair visible ahead.

Note: Special cases due to low visibility will be treated separately, i.e., only one gate visible (either ahead or astern), or two gates visible, one ahead, one astern.

(5) Derivation of Dynamic Situations. The process of navigation will include use of information that the

(a) Projected trackline is not parallel to the channel direction.

(b) That the actual trackline is not following that projected by the ship's heading, i.e., that leeway exists. This involves comparison of successive cross track error measurements with those projected by the trackline.

C.2.2.5 Information Anomalies

As a final note in the development of the process of navigation model information, the following anomaly must be taken into account. The angles ϕ_B and ϕ_R were defined, and the difference $\phi_B - \phi_R$ was suggested as the controlling "perceived" parameter for maintaining position within a channel. The statement "$\phi_B = \phi_R$ indicates position on the centerline" is true only if the relationship remains constant under dynamic conditions. The statements:

$$\phi_B > \phi_R = \text{Right of } ℄$$

$$\phi_B < \phi_R = \text{Left of } ℄$$

are not always true and are sensitive to the values of D (Distance to the gate), S (Aid Spacing) and D_B, D_R (Distances to the channel boundary.

As an example, consider the situation in Figure C.7. The vessel is approaching a gated pair and is significantly to the right of the centerline. In the figure:

$$\phi_B > \phi_R$$

$$D_B > D_R$$

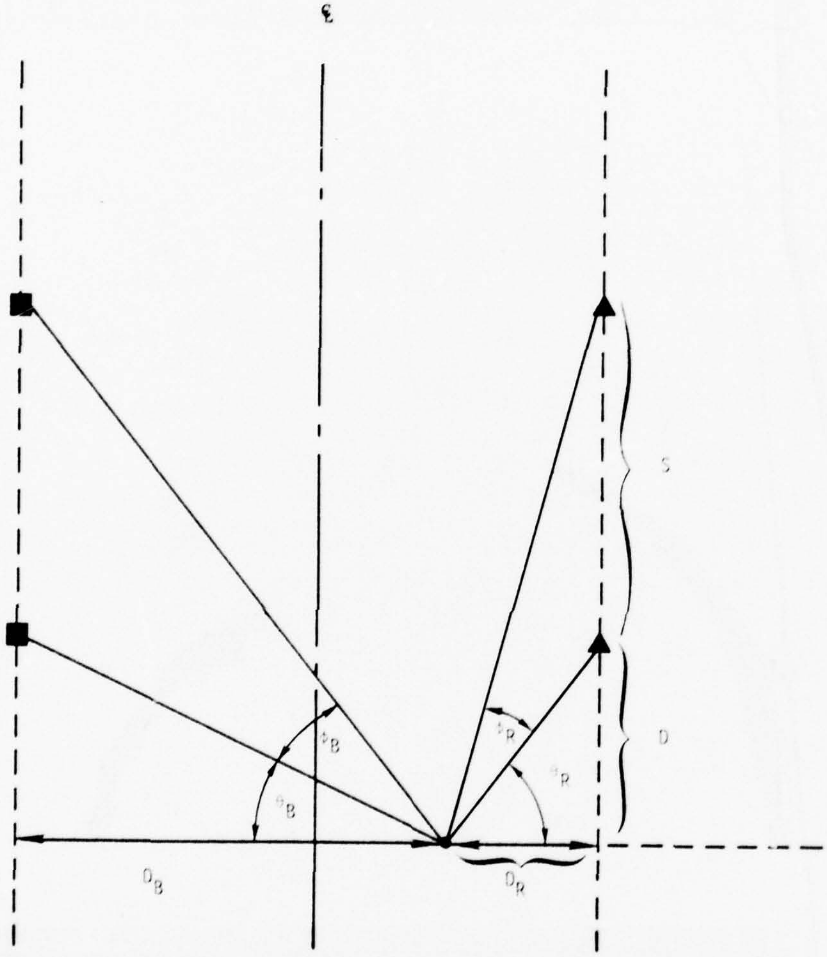


Figure C.7 Gated Configuration: $\phi_B > \phi_R$, Vessel Right of Centerline

Now consider Figure C.8. The vessel has moved into the gate and the inequalities are now:

$$\phi_B < \phi_R$$

$$D_B > D_R$$

i.e., the inequality between ϕ_B and ϕ_R has changed to the opposite condition. This obviously took place at some distance D from the gate where instantaneously $\phi_B = \phi_R$. Two conditions must be accounted for.

(1) An instantaneous $\phi_B = \phi_R$ will occur no matter where the trackline is with respect to the centerline. A continuous $\phi_B = \phi_R$ occurs only on centerline.

(2) The relationship between ϕ_B and ϕ_R will reverse sign as the vessel approaches the gate. The following statements apply:

(a) If initially $\phi_B < \phi_R$ and changes to $\phi_B > \phi_R$, then vessel track is left of centerline.

(b) If initially $\phi_B > \phi_R$ and changes to $\phi_B < \phi_R$, then vessel track is right of centerline.

C.2.3 The Single Gate Pair

The configuration which involves a pair of aids arranged in a single, "opposite side" pair is probably relatively rare. Three possibilities come to mind.

(1) A narrowing of a channel where only two "gates" are visible, but they are of different widths and hence the channel direction is not defined by the line joining buoys of like color, although the limits (boundaries) of safe water are marked.

(2) The situation existing at the entrance to a channel where only the first two aids (the first gate) are in sight.

(3) Low visibility conditions within a marked channel.

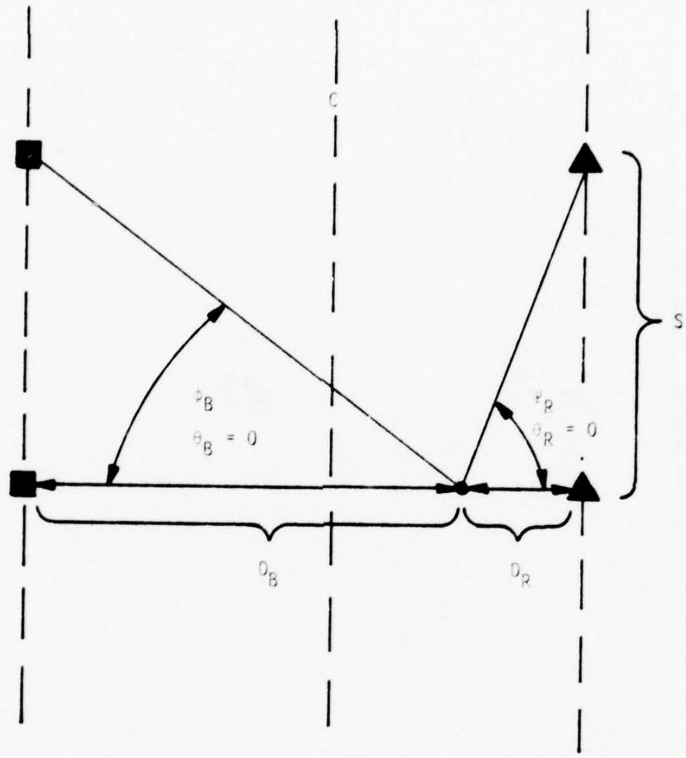


Figure C.8 Gated Configuration: $\phi_B < \phi_R$, Vessel to Right of Centerline

Figure C.9 illustrates the information available from a single gate wherein the intended track is perpendicular to the line joining the aids. Note that boundary lines are not defined.

Figures C.10a and C.10b illustrate cases where the desired approach to or exit from the gate are not perpendicular to the line connecting the aids.

From the point of view of information available from aids, the situations illustrated in C.10a and C.10b represent configurations with significantly less information available to the navigator in the form of guidance, than the situation wherein the navigator's desired track is perpendicular to the gate.

Figure C.11 illustrates the position and guidance parameters available.

C.2.4 Single Side Configurations (in Line Pairs)

We will define a "single side" configuration of aids as a configuration made up of in line aids only. The information available from such a configuration is, in the most basic form, a line defining direction and/or boundary.

(1) Position Parameters (Figure 12a). Based on the position of the aids, direct information available is the starboard danger boundary (for upbound vessels). The treatment is identical for downbound ships. Perceived information is available regarding the direction of the desired track as being parallel to the defined boundary. Position parameters yielding cross track error with respect to a desired track line are not available since, unlike the "gated" case, no trackline is defined. Position estimates are referrable only to the defined boundary line. In the process of navigation, the objective of the navigator would be to maintain a track parallel to the boundary line and a distance D_R from it.

Perceivable parameters yielding this information are shown in Figure C.9.

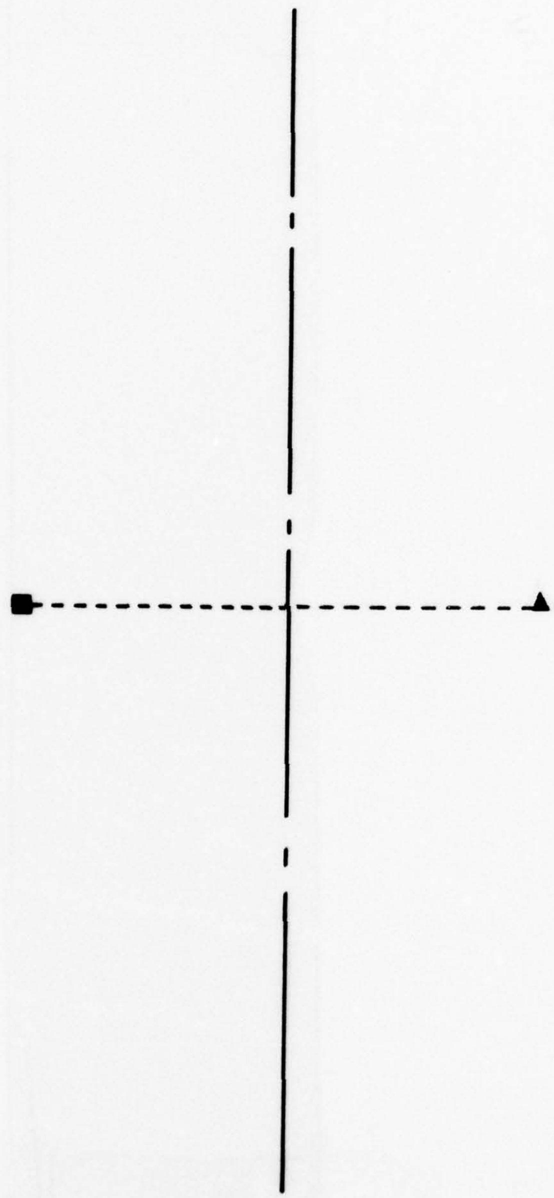


Figure C.9 Information Available from a Single Gated Pair

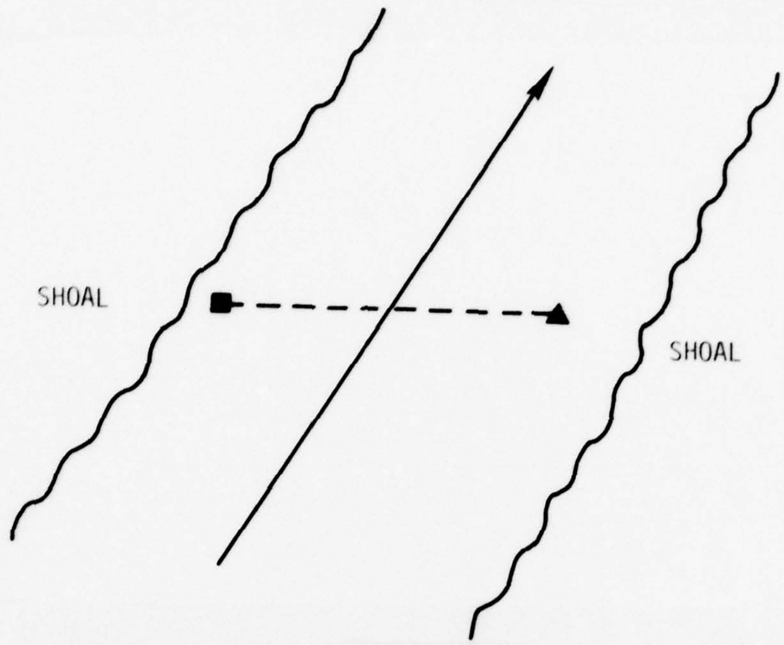


Figure C.10a

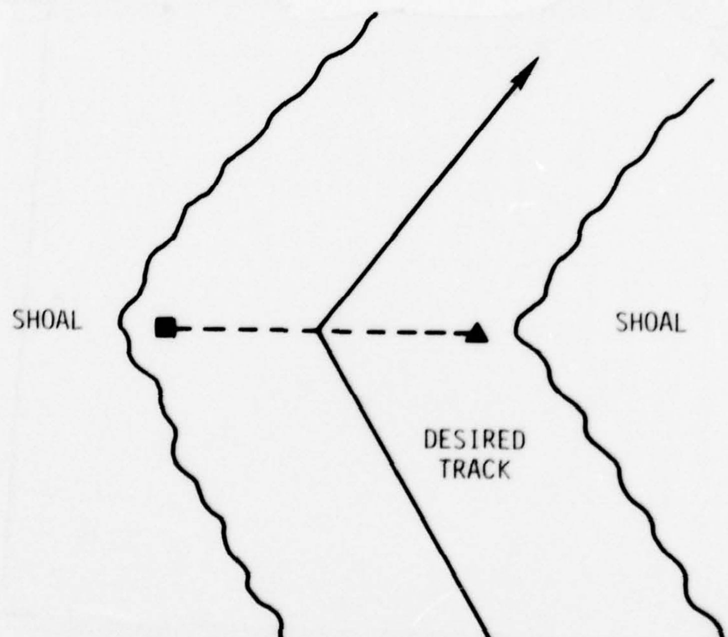


Figure C.10b

Figure C.10 Single Gate Configurations with Desired Track Not Perpendicular to Line Between Buoys

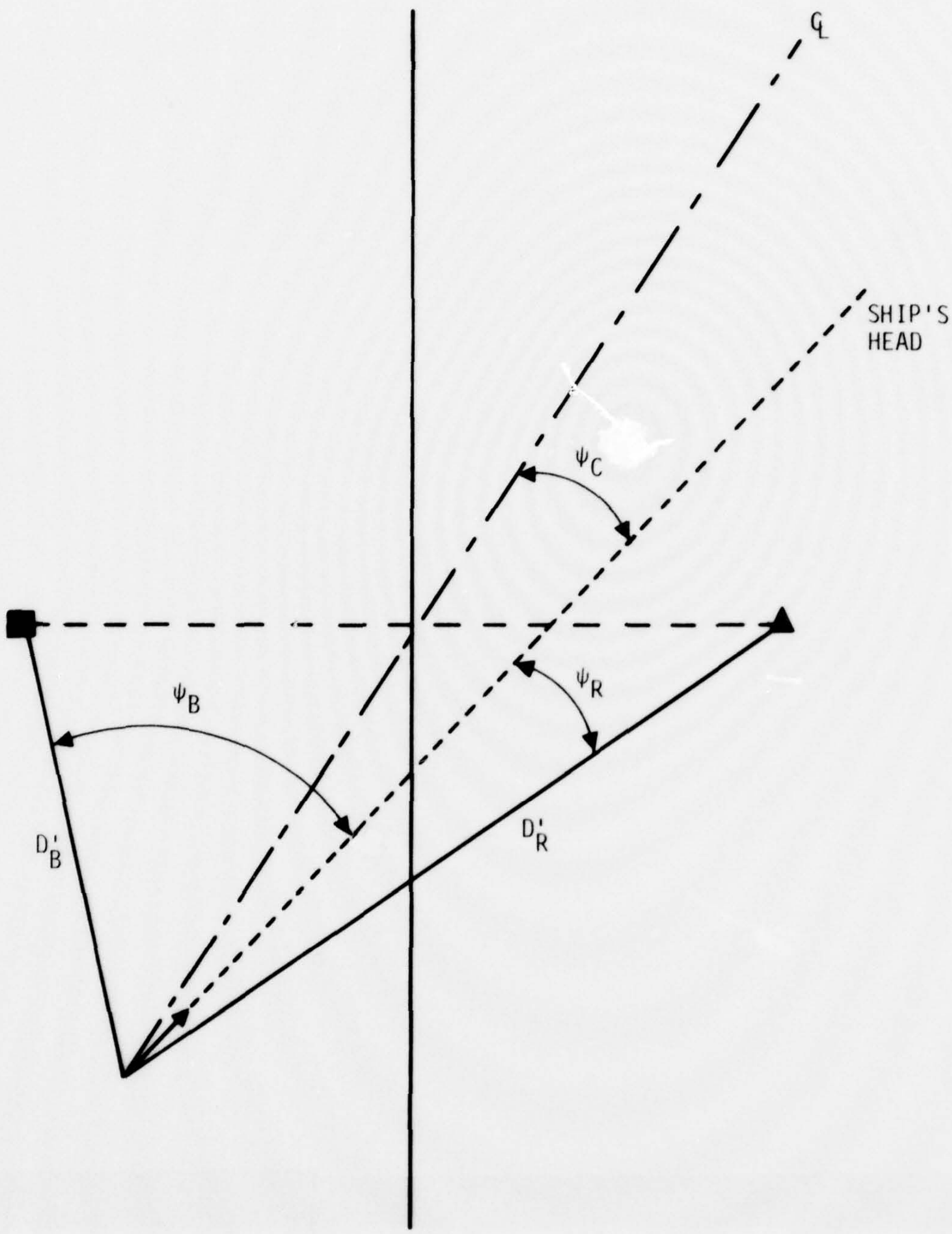


Figure C.11 Position and Guidance Parameters Available from a Single Gate

C.2.5 The Navigational Range

Publication CG-250-37 describes in some detail the parameters of design of a Navigational Range. The navigational range will be treated as a special case of the single side "in line" configuration of Paragraph C.2.4.

The navigation information available from a range is, as with other multiple configurations, a straight line, defined by the position of the two reference points of the range. Given the particular set of design parameters defined in CG-250-37, the parameters derivable from the information available are as shown in Figures C.13 and C.14. The symbology used will be consistent with that previously defined.

Derivable Parameters

(1) Positional (cross track) (Figure C.13)

ϕ_c = angle subtended of the observer by the two aids

θ_c = angle subtended by the nearest aid and the point on the centerline nearest the observer

D_c = distance off the centerline

W = aid spacing

D = distance of observer from the aid

It should be recognized the information derivable is no different from that discussed under "Gated Pairs," or "in line, single side," hence there is general similarity of the derivable information parameters. The differences are based on the straight lines which are defined, and on the process of navigation applied. A comparison with a "gated pair" will illustrate the similarities and differences.

(a) A Gated Pair defines the boundaries of safe navigation by the lines between buoys of like color. The centerline of the gated pair is "perceived" but not defined. The navigational range defines the centerline (hence the subscript c) but no boundaries are

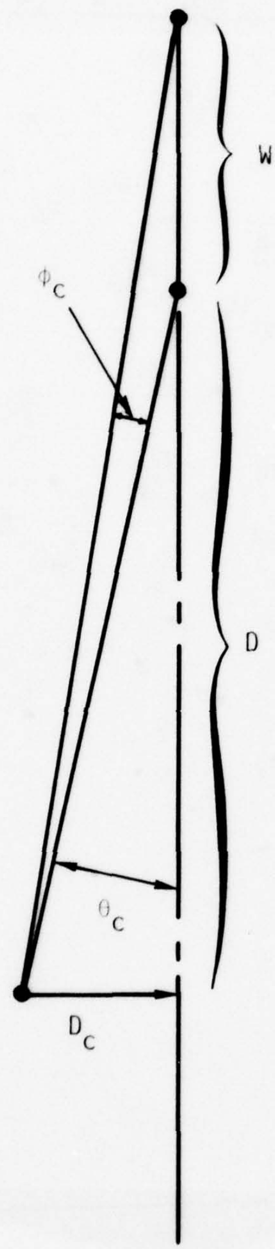


Figure C.13 Position Information Available from a Navigation Range

established other than those "perceived" by some maximum value of ϕ_c.

(b) In the range, the situation where D_c (cross track error) is zero is directly observable ($\phi_c = 0$) and in the process of navigation, the navigator's objective is to maintain this situation. In the gated pair, or single side case, the distance from the desired track is not directly observable but the distance D_B, D_R (distance from channel boundaries) can be estimated to a relatively high degree of accuracy in the "buoy abeam" condition.

The CG-250-37 adequately deals with the matter of parameter sensitivity (in its equation 18). Since the objective of this particular aid configuration is to define specifically the desired track, and the mariner's objective is to maintain that track, the "perceivable" parameter of paramount importance is the angle ϕ_c. for the estimation of cross track error D_c.

(2) Projected Track Information (Figure 14). As with any two-aid configuration, two parameters are available for use in projecting ship's track. In this case:

Ψ_1 = angle between ship's head and far range light

Ψ_2 = angle between ship's perceived head and near range light

In the process of navigation, the mariner would like to adjust his ship's head first, to cause ϕ_c to become zero (position on track line), and then maintain $\phi_c = 0$ by adjusting ship's head as needed. In the ideal case, the ship's head projected will coincide with the line defined by the range, i.e., no leeway is present. In the more usual case, as the vessel proceeds along the range, adjustments will be required such that Ψ_1 and Ψ_2 are non-zero, i.e., a "crab angle" is established.

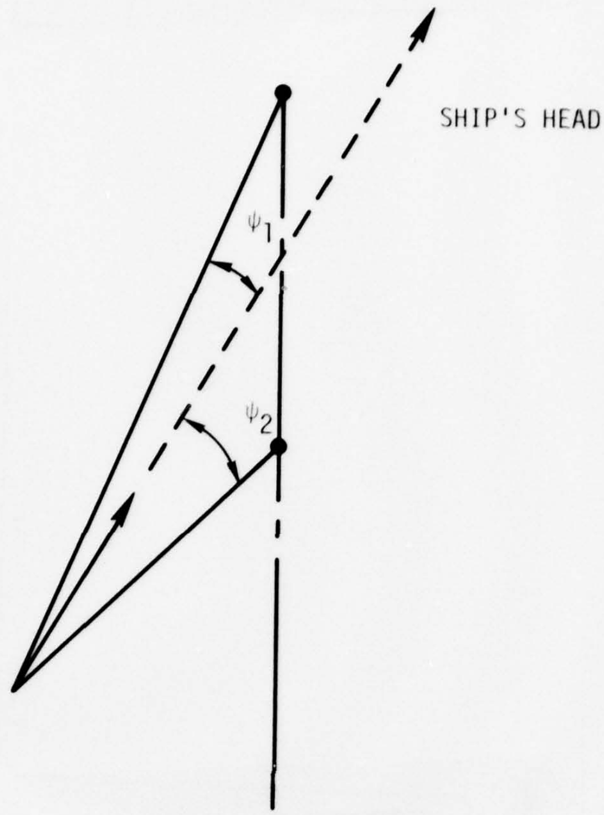


Figure C.14 Projected Track Information Available from a Navigation Range

C.2.6 Staggered Aid Configurations

Consideration of the information available in the form of derivable parameters for a staggered configuration of aids is probably the most complex in terms of the sensitivity of the available parameters and the fact that significant changes in the priority and form of the parameters appear to take place. Three different applications of the use of staggered aids appear to be:

(1) The existence of the "triplet" which stands by itself, independent of any other aids. Figure C.15 illustrates such a configuration.

(2) The possibility exists to reorganize available resources to reduce the number of aids available (or necessary), yet provide adequate information. Figure C.16 illustrates such a situation where a configuration of three gates is

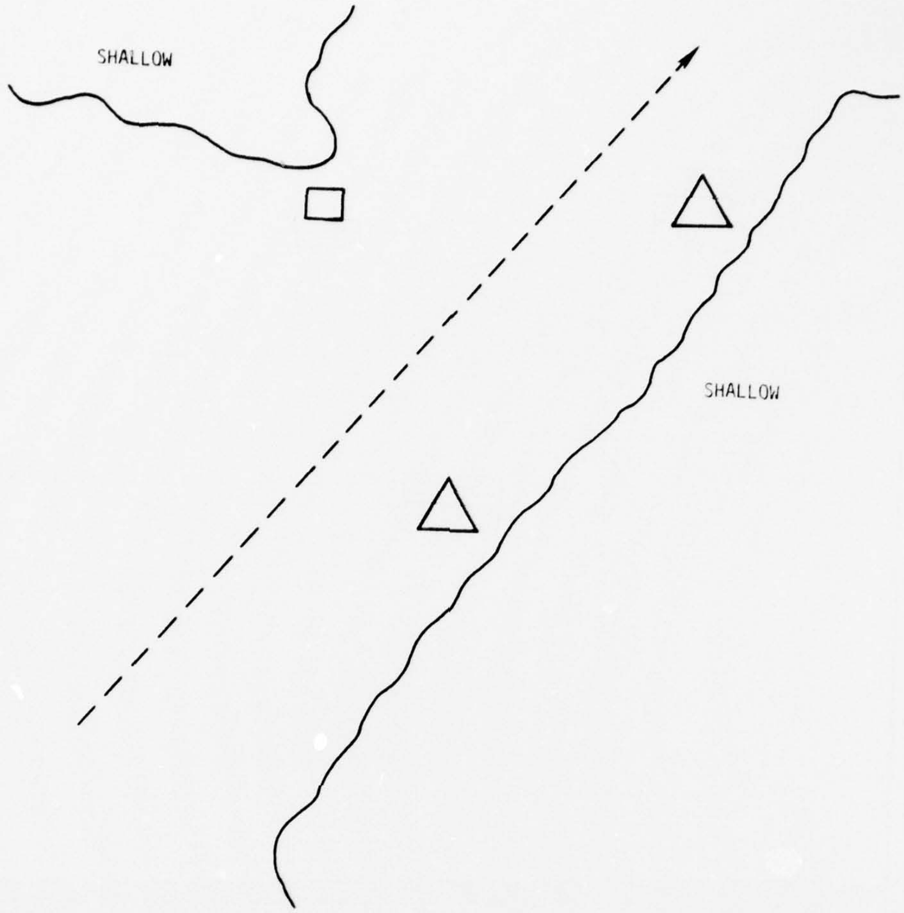


Figure C.15 Staggered Buoy Triplet

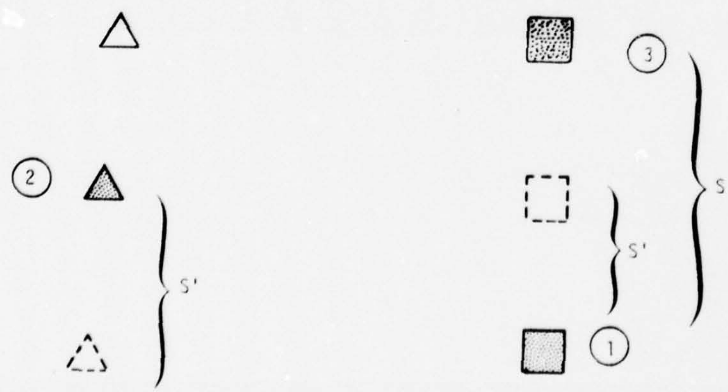


Figure C.16 Staggered Triplet As a Downgraded Gated Configuration

degraded to a staggered triplet covering the same length of channel. In this case, aid spacing between aids (S) of the same color is doubled, but the spacing (and hence time) between situations where at least one aid is abeam (S') remains the same. The objective would be to reduce the number of aids required to cover the same length of channel as the three gates (or double the length of channel which could be covered with the original number of aids). The test would be the measurement of degradation of information available vis a vis the accuracy requirements of the situation.

(3) A reorganization of two gates into two triplets essentially covering the same length of channel. The objective might be the improvement of available information. Popular opinion would have it that "gates" are superior to a staggered configuration. Figure C.17 illustrates that, in the staggered configuration the spacing between buoys of the same color (S) does not change but the distance (S') (and hence the time) between abeam situations is halved. This factor may be significant, depending on the sensitivity of the distance-off measurement when abeam versus the angular measurements.

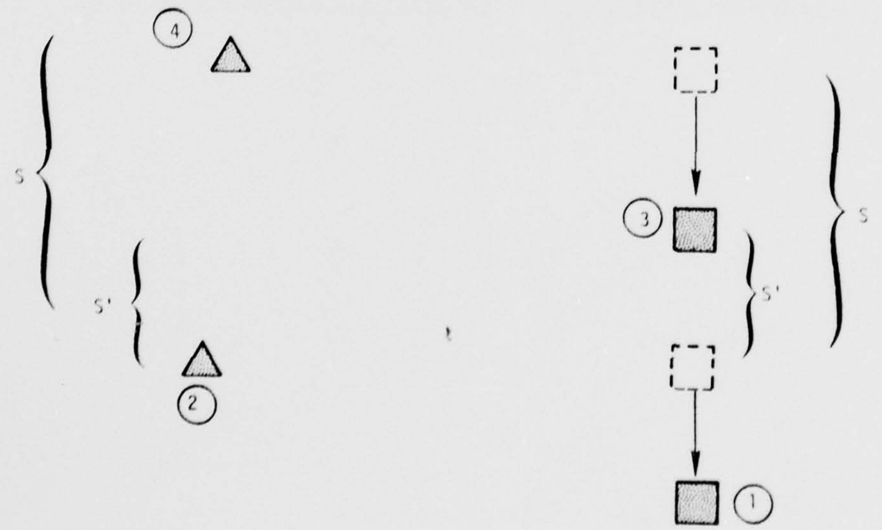


Figure C.17 Staggered Configuration Obtained by Shifting Buoys in a Gated Configuration

The parameters of the "Triplet" will be developed with reference to four situations. There may not be a significant difference among certain of the parameters, but four situations are required to illustrate parameter changeovers (priorities).

C.2.6.1 Positional Parameters

(1) Case 1 – Approach (Figure C.18). It may be noted that in Case 1, the derivable parameters are the same as for the gated pair, with one important addition, ϕ_{BR}. Secondly, the starboard boundary is defined for an upbound ship. The port boundary is undefined. Since the upbound ship will tend to favor the starbound side, this is an important factor to note since the defined boundary will change as the situation develops.

Parameters:

ϕ_{BR} – angle subtended by far aid of the "two-aid" side and the single aid

ϕ_R – angle subtended by the aids of the two-aid side

D_R – distance to starboard boundary, starboard boundary defined

E = error off centerline = $W/2 - D_R$

D_B = distance to port boundary, port boundary undefined

D'_B, D'_R = distance to nearest buoys

S' = S/2 = distance between abeam conditions

S = spacing of like colored aids

D = distance to abeam conditions

The scenario involves the approach to what could be called one "starboard" triplet, since the starboard boundary is defined. The mariners "perception" of E is probably a function of the following parameters, in order of significance.

(a) $\phi_{BR} - \phi_R$; ϕ_{BR} is a parameter unused in the gated case but is the only "port" side information available in this case.

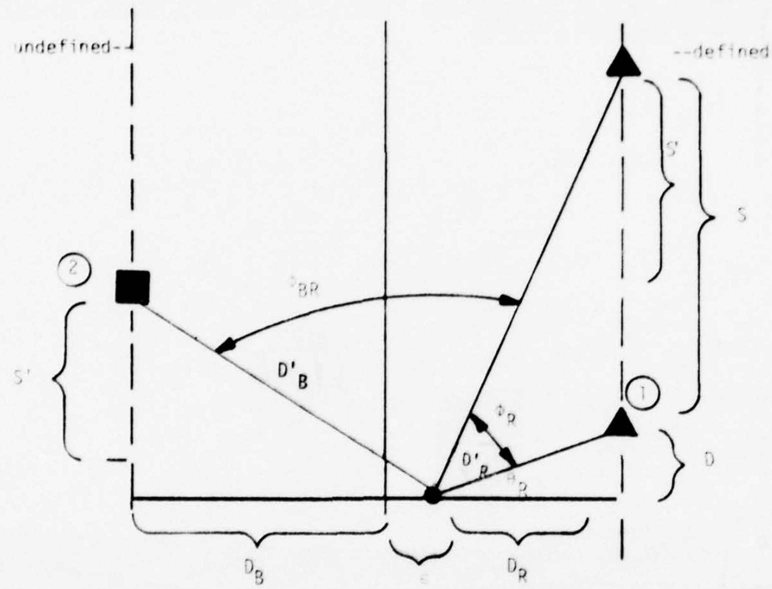


Figure C.18 Positional Parameters — Approach to the Starboard Side of a Triplet (Case 1)

(b) ϕ_R; ϕ_R yields the mariner's perception of the only defined boundary. In the approach situation, a small ϕ_R and relative larger ϕ_{BR} would be the operative combination.

(c) D'_B - D'_R; Unlike the gated case, the port boundary is <u>undefined</u>. Hence measurements of relative distance to the boundaries

$(D_B - D_R)$ are less important than actual perceivable distance D'_B and D'_R. As the distance D decreases, this measurement probably increases in priority.

The cross track error, either in terms of D_R or $E = W/2 - D_R$ should be related to:

$$(\phi_{BR} - \phi_R),\ \phi_R,\ D,\ S,\ S'.$$

(2) Case 2 – Abeam of Aid on the Defined (Starboard) Side (Figure C.19). As the buoy on the defined side of the channel comes abeam, D'_R collapses to equal D_R. The relative size of $\phi_{BR} - \phi_R$ probably becomes less important since, in coming abeam, ϕ_R has opened. It must be determined where, as D decreases, the measurement D'_R becomes the more significant. At the point illustrated in Figure C.19, the estimate of D'_R is most accurate. The parameters, in order of importance, are:

$$D_R$$

$$D'_B - D_R$$

$$\phi_{BR}$$

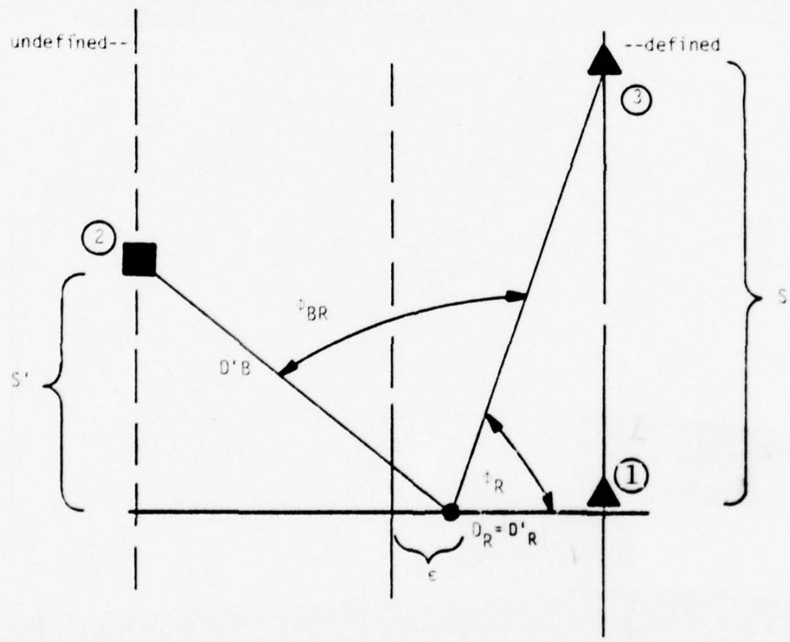


Figure C.19 Position Parameters – Abeam of the Aid on the Defined Side (Case 2)

(3) Case 3 – Approaching the Port Side Triplet (Figure C.20). In case 3, the mariner is approaching a new triplet (2,3,4) and departing the previous one (1,2,3).

Important parameter changes now take place requiring a shift in mental perception.

(a) ϕ_{BR} is now ϕ_{RB} with the red side of the channel single buoyed.

(b) The port hand side of the channel is now defined. This amounts, in the case of the upbound mariner, to a certain degradation in the significance of the available information. He is primarily concerned with the starboard side, since this is presumably his "allocated half." Unless the model sticks strictly to centerline information (which it cannot if there is other vessel traffic in the channel), consideration must be taken of the fact that, since the mariner is concerned with his "half," the order of priority and sensitivity of his perceptions may be entirely different from that when "his own boundary" is the defined one.

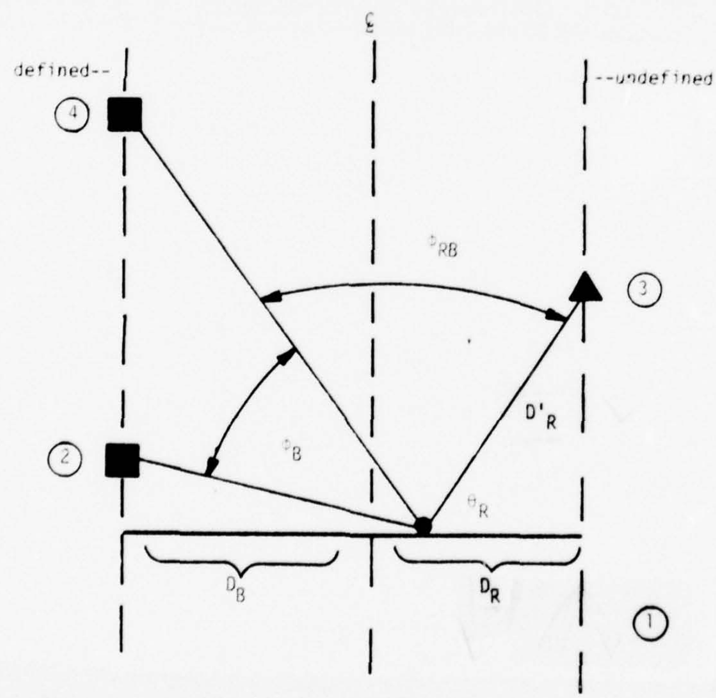


Figure C.20 Approach to the Port Side of a Triplet (Case 3)

In order of priority, the mariner will probably use the following:

(a) $\phi_{RB} - \phi_B$. This measurement, while still the highest in priority, will be less sensitive because ϕ_B cannot be kept small (or as small) as in the previous case.

(b) D_R, D'_R. His interest now is in not permitting D_R to go to zero (out of channel). θ_R and D'_R are the parameters of interest in this regard.

From the point of view of Position Information Available, this is the worst case. Projected track and ship's head information will be an important input to the process of navigation at this point.

(4) Case 4 – Abeam of the "Off Side" Buoy (i.e., Abeam of Buoy 2) (Figure C.20). All the comments of Case 2 apply to Case 4, with all the caveats of Case 3. The parameters used will be the same with ϕ_{RB}, ϕ_B, D_B probably controlling.

C.2.6.2 Projected Track Information

Information from aids in the staggered configuration which can be "perceived" as derivable parameters when compared with the ship's head (compass, shipboard leading line) follows essentially the development for the gated configuration, with similar exceptions. Only two cases will be illustrated, the approach to triplet 1,2,3 and the approach to triplet 2,3,4. The application of the "abeam" cases is not significantly different since, as with the abeam case in the gated pairs, there will still be two aids forward of the beam which permit derivation of the controlling parameter. The difference between the two cases treated lies in the fact that, as with positional information, the available parameters change when proceeding through triplet 1,2,3 into triplet 2,3,4.

(1) Case 1 – Approach to Triplet 1 (Figure C.21). The available parameters derivable from a comparison of the aid information with the perceived ship's head are as follows:

Ψ_B – Angle between ship's head and "off side" buoy

Ψ_{R1} – Angle between ship's head and far buoy of the visible pair

Ψ_{R2} – Angle between ship's head and near buoy of the visible pair

There appears no relatively simple relationship among the angles defined with respect to projected track, as there is with a gated pair. In the process of navigation, under "normal" circumstances (i.e., no extreme leeway), $\Psi_{R2} > \Psi_{R1}$ would pertain to prevent projecting the track beyond the established boundary. On the centerline, the condition $\Psi_{R2} > \Psi_{R1}$ would pertain if the ship's head were directed along that line until the near buoy came abeam. The sensitivity of this condition versus off centerline positions should be checked.

The parameters available may be used to detect leeway. As the vessel proceeds, all angles, Ψ_B, Ψ_R, Ψ_{R2} should increase. A perception of a decrease in any of these angles would indicate the necessity for the application of a "crab angle." The application of such a crab angle should result in a change in the absolute values of the Ψ's, but the relative change should cause all to increase as the vessel proceeds, i.e., the forces causing the detected leeway are counteracted. The application of a crab angle negates the condition that $\Psi_{R2} > \Psi_{R1}$. Ψ_{R1} may, for example, change sign such that instead of $\phi_R = \Psi_{R2} - \Psi_{R1}$, the condition would be $\phi_R = \Psi_{R2} + \Psi_{R1}$.

In such a case, the far buoy defining the channel boundary would be on the "wrong" side of the bow; a condition which, in Europe, was said to have occurred in the entrance to Rotterdam under certain current and wind conditions. According to the U.S. interviews, the limit on such a crab angle would be 15°. The application of this limit to the change in the parameters might result in some total limit on the parametric changes.

In summary, the ideal case in approaching a triplet (on the centerline, directed along the center) would dictate that $\Psi_{R2} > \Psi_B > \Psi_{R1}$ at all times.

Exceptions to this *arise when perceived positions are* not on the centerline, and/or perceived ship's head is not directed in the direction of the centerline.

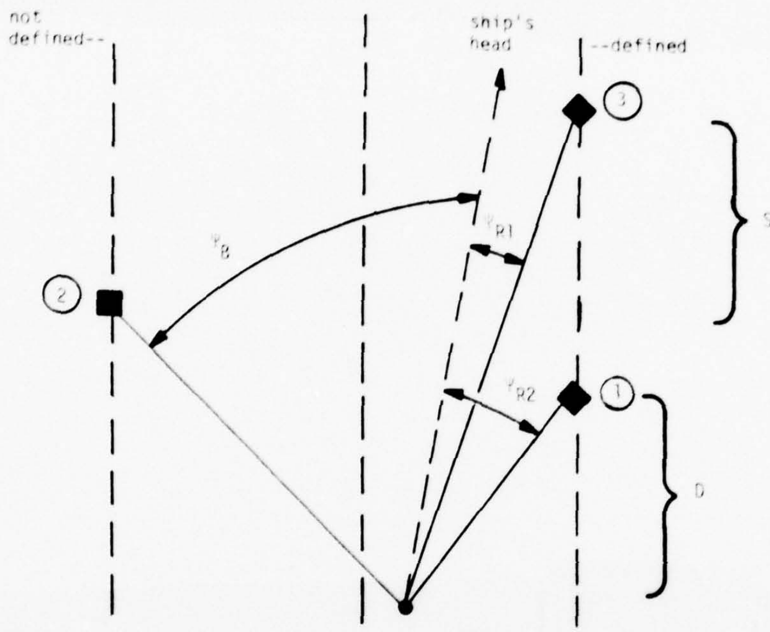


Figure C.21 Projected Track Information — Approaching the Starboard Side of a Triplet

(2) Case 2 – Approach to Triplet 2 (Figure C.22). Figure C.22 is included in the discussion simply to illustrate the reversal in available parameters and again to note that the information perceivable with respect to the port-based buoys, while the same parametrically as in the previous case, are referred to the "other" side of the channel.

The previous discussion has pointed out the fact that the available parameters "change sides" as the mariner proceeds along a channel marked with staggered buoys. Since the accuracy of the estimation process depends, to an extent, on the distance from the defined boundary, it would appear beneficial to examine the difference in the gated versus staggered configuration from the point of view of symmetry. In the staggered case, it might be found that

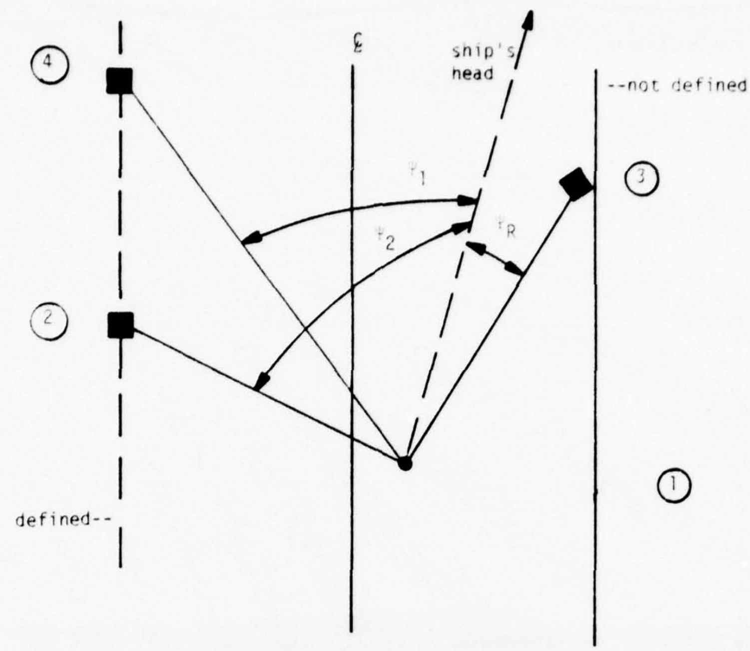


Figure C.22 Projected Track Information – Approaching the Port Side of a Triplet

the accuracy of the entire process will vary in a different way. For example, in the two-gated case, with any desired extension, both channel boundaries are continuously defined by the aid configuration. In the staggered case (considering only one triplet in use at any one time), the boundaries are alternately defined.

The results may place limits on spacing such that, if a staggered configuration is to be used, then, as in the double gated case, the establishment criterion would call for four aids visible ahead under "average" visibility conditions.

C.2.7 The Four Aid Staggered Configuration

A necessary part of the analysis of staggered aid configurations is the configuration where four aids are in sight ahead. The

fixed parameters for such a configuration (assuming symmetry) are

S = Spacing between aids of like color

S/2 = Spacing between "abeam" situations

3S/2 = Total channel length covered

Ultimately, it will be interesting to test the parameters S and S/2 against a gated set of aids with spacing S, and in the extreme case, to compare a staggered configuration with spacing of 2S between aids of the same color (S between abeam positions) and a gated set of spacing S, covering one half the amount of channel with the same number of buoys. Figure C.23 illustrates the configuration and the perceived parameters derivable for cross track position estimation.

C.3 INFORMATION USED IN SAMPLE WATERWAY CONFIGURATIONS

C.3.1 Introduction

The process of navigation is directly related to the waterway configuration and the information available from the aids to navigation. Sections C.1 and C.2 presented detailed data regarding information derivable from basic "building block" aid configurations. Section C.3 presents the method whereby this information can be expanded to form harbor elements, information parameters defined with an assigned priority, and constraints imposed to vary the process of navigation through the element.

C.3.2 Definitions

Table C.1 defines the information parameters as developed in Section C.2. These parameters are also depicted in Figures C.24 and C.25. Some difference in symbology will be noted. This is

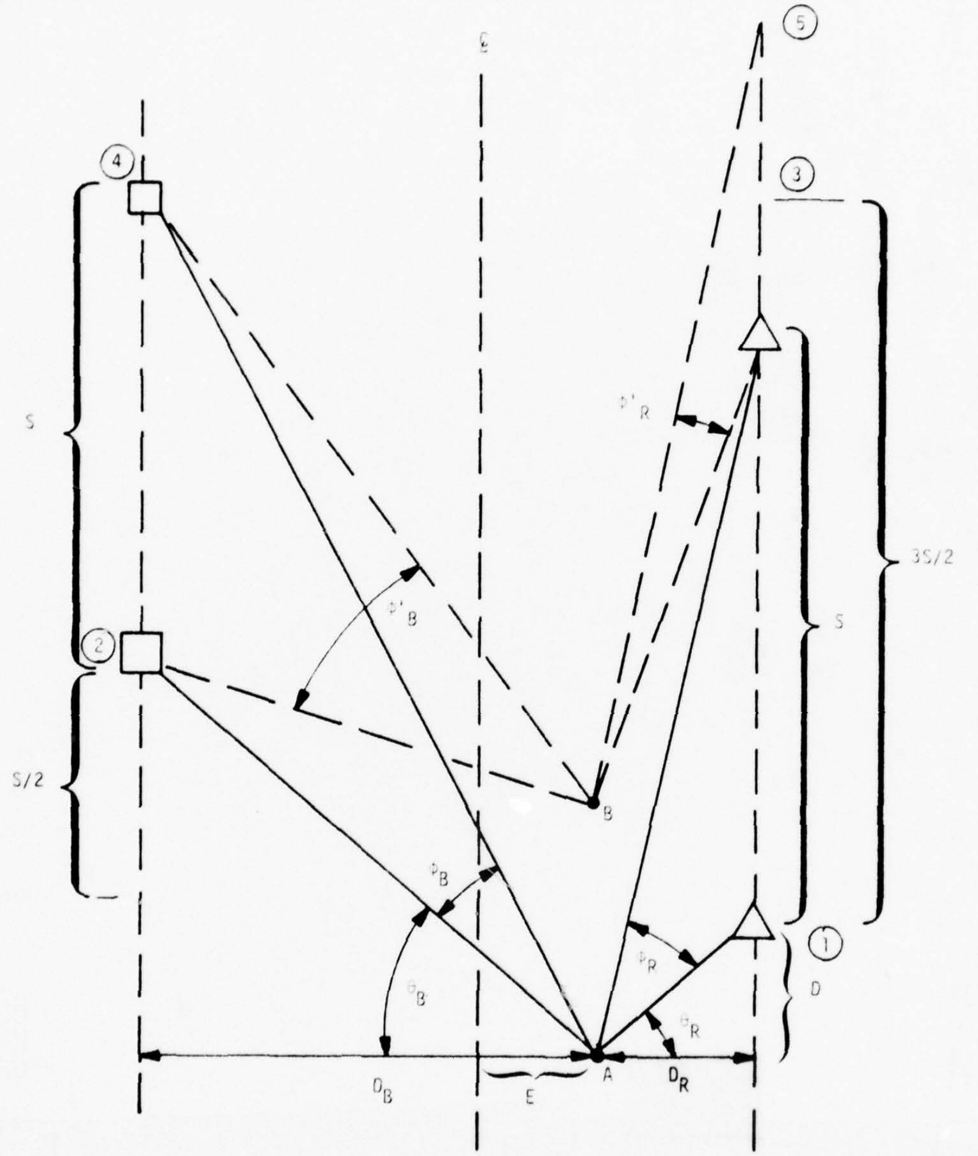


Figure C.23 Position Information for a Four-Aid Staggered Configuration

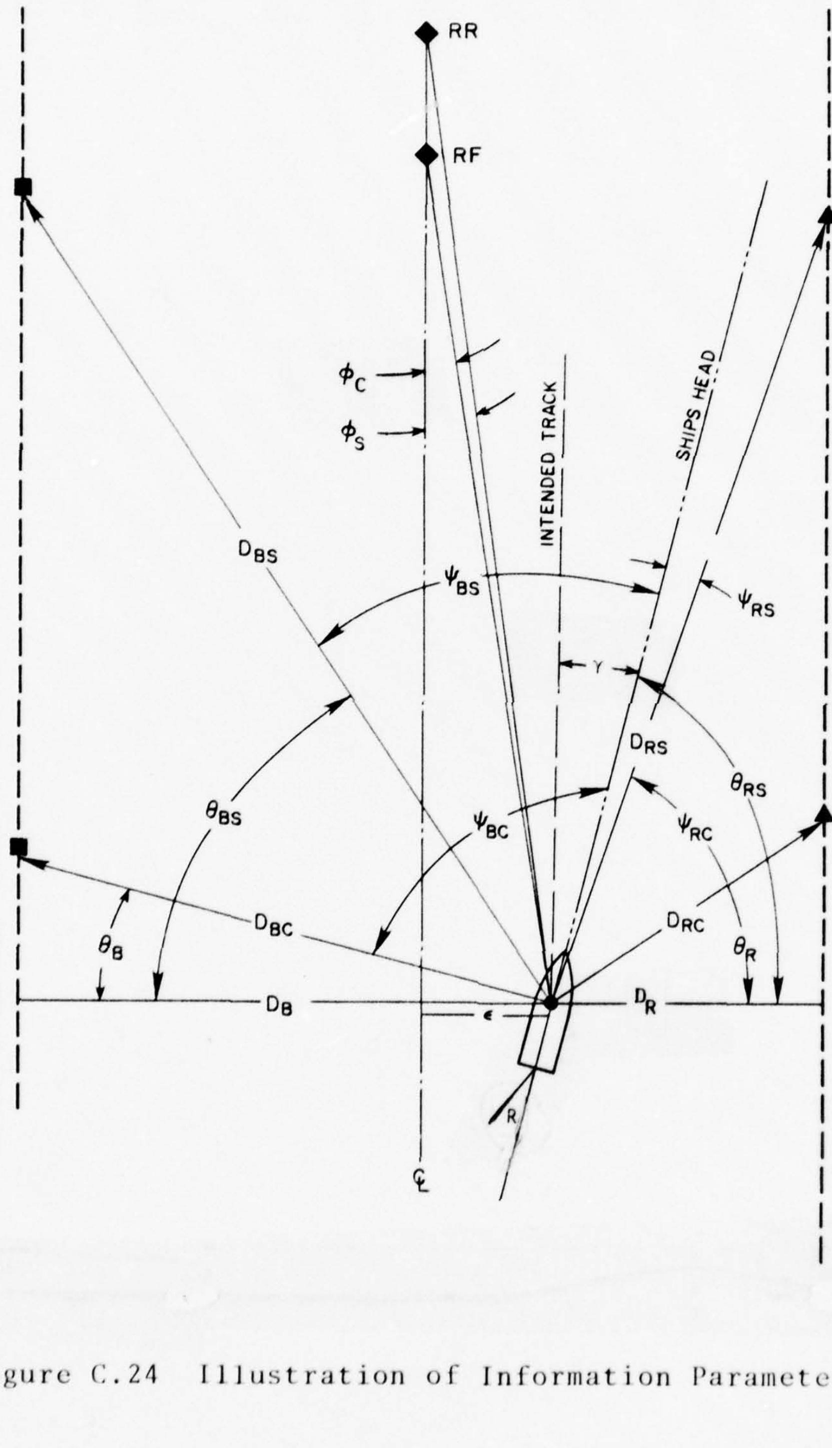


Figure C.24 Illustration of Information Parameters

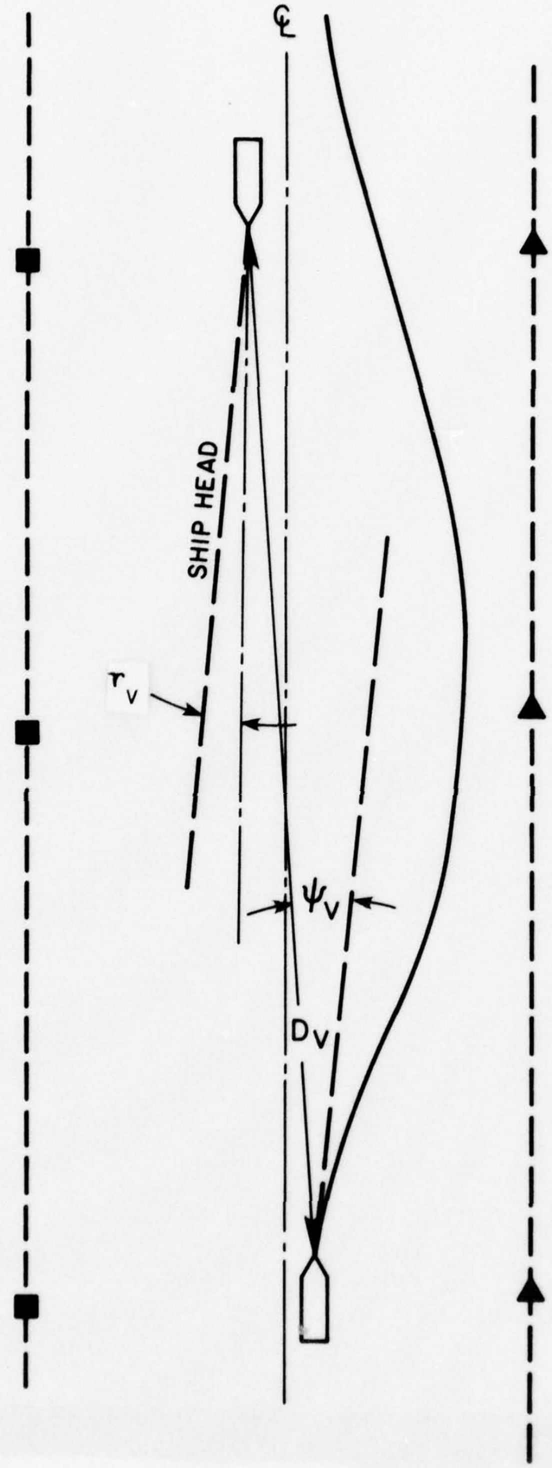


Figure C.25 Illustration of Information Parameters (Relative to Another Vessel)

necessary to accommodate the expansion of the basic configurations into synthesized harbor modules.

The following definitions are provided to facilitate interpretation of the "information used" tables to be presented.

(1) Terminology

Upbound	=	a vessel transit with red to right
Downbound	=	a vessel transit with black to right
Opening	=	an angle which is increasing
Closing	=	an angle which is decreasing

(2) Table Headings

(a) Figure Number — Related to aid configurations 1 through 16 (Figures C.26 — C.41)

(b) Transit Number — Each transit will have different conditions and possibly different processes of navigation

(c) Entrance Conditions —

γ - The crab angle at the entrance based upon the mariner's estimate of the anticipated effect of wind and current or the result of an exit from an unspecified prior harbor module

ε - The location of the vessel at the module entrance. (+) indicates to the right of ℄; (-) indicates to the left.

(d) Heading — Degrees True, vessel over the ground

(e) Intention — Intended method of transit

(f) Location — Within a specific harbor module, the location of the vessel when the succeeding columns are filled out. Reference is to the aid numbering in the figure as follows:

#4 — A beam of aid #4

4/5 — Between aids 4 and 5

4-6 – midway between aids 4 and 6

4→6 – on a line extending from 4 and 6

Note: The transit tables will list the red or black aids by number, e.g., D_8 is the distance to #8. This is for ease in referring to the figures.

(g) Longitudinal Position Measurement – The method used by the mariner to estimate his present position longitudinally in the channel. This may include terminology such as:

aid count (AC) – Counting the aids from the entrance or identifying the aid number

D_T – Estimating the distance to the farthest aid in the harbor module

SP x T – "speed x time" estimate of distance traveled

(h) Lateral Position Measurement – The method of estimating present lateral vessel position. Terminology may include:

$D_R - D_B$ = Difference in distance to nearest aids

ε = distance off centerline

$\theta_R - \theta_B$ = difference in angles

$\psi_{RC} - \psi_{BC}/\psi_{RS} - \psi_{BS}$ = Comparing the difference of the angles between two aid groups

(i) Longitudinal Rate Measurement – Method of estimating rate of change of longitudinal position for purposes of guidance. This may include:

SP – Vessel speed

S/t – Aid spacing divided by time

ΔD_T – Change of distance to farthest aid

(j) Lateral Rate Measurement – Method of estimating cross track rate for guidance including:

$\Delta(D_R/D_B)$ = Difference in vessel's position as the transit proceeds from one aid to the next (or aid pairs)

$\Delta\varepsilon$ = Difference in off centerline position between one aid (pair) and the next aid (pair)

$\psi_{RC} - \psi_{RS}$ = Rate of angle opening between two aids

(k) Turn Indicator – Estimate of information used to turn or initiate a course correction, including:

#7→9 – Commencing the turn when aids 7 and 9 form a range

#7→9,ADV – Commencing the turn before 7 and 9 form a range by an amount equal to vessel advance

(l) Notes – Will describe any circumstances which might not be covered in the general terminology, or a condition of the vessel which dictates mariner action.

C.3.3 Information Presented in the Tables

Tables C.2 through C.14 present transit information for a vessel proceeding through each of the harbor module configurations shown in Figures C.26 through C.41. In effect, the tables present "technique" in essentially the same form that is used by the PON model. For example, consider the first three entries in Table C.3. The harbor module is that represented by Figure C.27, a straight channel bounded on only one side by a "single side" configuration (discussed in Section C.2.4). The initial location of the vessel is varied from the entrance (Transit 2A), to a position between buoys 2 and 4 (Transit 2B), to a position abeam of buoy 4 (Transit 2C). Under the stated conditions, the table then presents the aid to navigation information which inputs to the mariner's "state estimate" in terms of the column headings. Notes referred to in the last table column refer to the information in Section C.4, "Explanatory Notes."

Table C.2

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
26	1A	0	0	000	℄ $\pm$ .2W	Entrance	SPxT	D_t	$\phi_c-\phi_s=0$	None	Sp	None	None	None	None	None	1
	1B					Any	SPxT	D_t	$\phi_c-\phi_s\neq 0$	None	Sp	ΔD_t	$\Delta(\phi_c-\phi_s)$	$\Delta\phi_c$	$\Delta\phi_s$	$\Delta(\phi_c-\phi_s)$	1
26	2A	7^o Left	+150'	000	℄ + 150' (-50,+100)	Entrance	SpxT	D_t	$\phi_c-\phi_s\neq 0$	None	Sp	None	None	None	None	None	2
	2B					Any	SpxT	D_t	$\phi_c-\phi_s\neq 0$	None	Sp	ΔD_t	$\Delta(\phi_c-\phi_s)$	$\Delta\phi_c$	$\Delta\phi_s$	$\Delta(\phi_c-\phi_s)$	2
26	3A	7^o Left	+150'	000	℄ + 150' (-50,+100)	Entrance	SpxT	D_t	$\Psi_c-\Psi_s\neq 0$	None	Sp	None	None	None	None	None	3
	3B					Any	SpxT	D_t	$\Psi_c-\Psi_s\neq 0$	$\phi_c-\phi_s\neq 0$	Sp	ΔD_t	$\Delta(\Psi_c-\Psi_s)$	$\Delta(\phi_c-\phi_s)$	$\Delta\Psi_c$	$\Delta(\Psi_c-\Psi_s)$	3
27	1A	0	0	000	℄ (-50,+100)	Entrance	AC	SpxT	D_2	None	Sp	None	None	None	None	None	
	1B					#2-4	D_{Bc}	SpxT	$\theta_4-\theta_6-\theta_8$	D_B	$\Delta\dot{D}_{Bc}$	Sp	$\Delta(\Psi_{Bc}-\Psi_{Bs})$	$\Delta\Psi_{Bc}$	None	$\Delta(\Psi_{Bc}-\Psi_{Bs})$	4
	1C					#4	AC	SpxT	D_4	$\theta_6-\theta_8$	S/t	ΔD_{Bc}	$\Delta(D_B/D_B)$	$\Delta(\Psi_{Bc}-\Psi_{BS})$	None	$\Delta(D_B/D_B)$	

Table C.3

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
27	2A	0	-50'	000	℄ (-50,+100)	Entrance	AC	SpxT	D_2	$\theta_5-\theta_8$	Sp	None	None	None	None	None	
	2B					#2-4	D_{Bc}	SpxT	$\theta_4-\theta_6-\theta_8$	D_3	ΔD_{Bc}	Sp	$\Delta(\Psi_{Bc}-\Psi_{BS})$	$\Delta\Psi_{Bc}$	$\Delta\phi_{10}$	$\Delta(\Psi_{Bc}-\Psi_{BS})$	5
	2C				D_{10}	#4	AC	SpxT	D_4	$\theta_5-\theta_8$	$S/_t$	ΔD_{BC}	$\Delta\phi_{10}$	$\Delta\Psi_{10}$	$\Delta(\Psi_{Bc}-\Psi_{BS})$	$\Delta\phi_{10}$	6
27	3	0	0	180	℄ (-150,0)	Note 7→											7
27	4	0	+50'	180	℄ (-150,0)	Note 8→											8
28	1A	0	0	000	℄ (-50,+100)	Entrance	AC	SpxT	D_2	$\theta_3-\theta_4$	Sp	None	None	None	None	None	9
	1B					#2-4	D_4&D_5	SpxT	$\theta_4-\theta_6-\theta_5$	ε	ΔD_4& ΔD_5	Sp	$\Delta(\Psi_4-\Psi_5)$	$\Delta(\Psi_{10}-\Psi_{11})$	$\Delta(\Psi_4-\Psi_6)$	$\Delta(\Psi_4-\Psi_5)$	
	1C					#4/5	AC	SpxT	D_4-D_5	$\theta_4-\theta_6-\theta_8$	S/t	Sp	$\Delta(D_2-D_4/D_5)$	$\Delta(\Psi_{10}-\Psi_{11})$	$\Delta(\Psi_6-\Psi_8)$	$\Delta(D_2-D_4/D_5$	
	1D					#6	AC	SpxT	D_6	$\theta_8-\theta_{10}-\theta_{11}$	$S/_t$	Sp	$\Delta(D_4/D_5-D_6)$	$\Delta(\Psi_{10}-\Psi_{11})$	$\Delta(\Psi_8-\Psi_{10})$	$\Delta(D_4/D_5-D_6$	
	1E					#8	AC	SpxT	D_8	$\theta_{10}-\theta_{11}-\theta_{12}$	S/t	Sp	$\Delta(\Psi_{10}-\Psi_{11})$	$\Delta(D_6-D_8)$	$\Delta(\Psi_{10}-\Psi_{12})$	$\Delta(\Psi_{10}-\Psi_{11})$	

Table C.4

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ϵ				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
29	1A	0	+150	000	$\mathcal{L} \pm 100'$	Entrance	AC	SpxT	D_1-D_2	$\theta_3-\theta_4$	Sp	None	None	None	None	None	
	1B					#1-3	D_3-D_4	SpxT	$\theta_4-\theta_6$ & $\theta_3-\theta_5$	D_3/D_4	ΔD_3 & ΔD_4	S/t	$\Delta(\Psi_3-\Psi_4)$	$\Delta\tilde{\phi}$ D_3-D_4	$\Delta(\Psi_5-\Psi_6)$	$\Delta(\Psi_3-\Psi_4)$	10
	1C					#3	AC	SpxT	D_3-D_4	$\theta_5-\theta_6$	S/t	Sp	$\Delta(D_1-D_2/D_3-D_4)$	$\Delta(\Psi_5-\Psi_6)$	$\Delta\tilde{\phi}$ D_5-D_6	$\Delta(D_1-D_2/D_3-D_4)$	
30	1A	0	+100	000	$\mathcal{L}_L{}^{+.2\omega}_{-.1\omega}$	Entrance #2	AC	D_3	$\theta_3-\theta_5$, θ_4	None	Sp	None	None	None	None		
	1B					#2-3	AC	D_3	$\theta_3-\theta_5$, $\theta_4-\theta_6$	None	Sp	ΔD_3	$\Delta(\Psi_3-\Psi_5, \Psi_4-\Psi_6)$	ΔD_R	$\Delta\tilde{\phi}$ D_4-D_5	$\Delta\Psi_3$	
	1C					#3	AC	D_4	$\theta_5-\theta_6$, θ_4	D_3	Sp	$S/2t$	$\Delta(D_2/D_3)$	$\Delta\Psi_4$	$\Delta\Psi_5$	$\Delta(D_2/D_3)$	
	1D					3-4	AC	D_4	$\theta_4-\theta_6$ $\theta_5-\theta_7$	D_4	Sp	ΔD_4	$\Delta(\Psi_4-\Psi_6, \Psi_5-\Psi_7)$	$\Delta\Psi_5$	$\Delta\Psi_4$	$\Delta\Psi_5$	
31	1A	7° Left	+150	000	$D_5=D_6$	Entrance	AC	D_4	D_1-D_2	$\theta_3-\theta_4$	SP	None	None	None	None	None	
	1B					4→6	D_4	D_3	4 →6 θ_3	None	$\Delta(\Psi_4-\Psi_6)$	ΔD_4	$\Delta(\Psi_4-\Psi_6)$, $\Delta\Psi_3$	$\Delta(\Psi_3-\Psi_5)$	None	4→ 6	11
	1C					3-4	AC	D_5	D_3-D_4	θ_5	Sp	$\Delta\theta_3$, $\Delta\theta_4$,	$\Delta(D_3-D_4)$	$\Delta\Psi_5$	$\Delta\Psi_6$	$\Delta\Psi_5$	
	1D					4/6	D_5	D_6	$\theta_5-\theta_6$	D_R	$\Delta(D_5)$	ΔD_6	$\Delta(\Psi_5-\Psi_6)$	$\Delta\Psi_5$	None	$\Delta\Psi_5$	

Table C.5

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
32	1A	7^o Left	O	000	$D_8=\cancel{L}$ + 100,-50.	Entrance #2	AC	D_3	D_2	$\theta_3-\theta_4$ θ_2	Sp	None	None	None	None	Ψ_3	
	1B					2-3	D_3	D_4	$\theta_3-\theta_5$ θ_4	None	Sp	ΔD_3	$\Delta(\Psi_3-\Psi_5,$ $\Psi_4)$	$\Delta(\Psi_4-\Psi_8,$ $\Psi_3)$	None	$\Delta\Psi_3$	
	1C					#3	AC	D_4	D_3	$\theta_4,$ $\theta_5-\theta_7$	Sp	ΔD_4	$\Delta(\Psi_4-\Psi_8)$	$\Delta\Psi_4$	$\Delta(\Psi_4-\Psi_5)$	$\Delta\Psi_4$	
	1D					4→8	4→8	D_4	$\theta_4-\theta_8,$ θ_5	$\theta_4,$ $\theta_5-\theta_7$	$\Delta(\Psi_4-$ $\Psi_8)$	ΔD_4	$\Delta(\Psi_4-\Psi_5)$	$\Delta(\Psi_5-\Psi_7)$	None	$\Delta(\Psi_4-\Psi_8)$	
	1E					4→5	AC	D_7	D_4-D_5	$\theta_7-\theta_8$	Sp	ΔD_7	$\Delta(\Psi_7-\Psi_8)$	$\Delta(\Psi_7-\Psi_8)$	None	$\Delta\Psi_7$	
						#7	AC	D_8	D_7	None	Sp	ΔD_8	$\Delta(D_4-D_5,$ $D_7)$	None	None	$\Delta\Psi_8$	
32	2A	3^o Right	O	135^o	$D_2=150$ +0,-100	Entrance #8	AC	D_7	D_8	$\theta_5-\theta_7,$ θ_4	Sp	None	None	None	None	Ψ_4	
	2B					#7	AC	D_4	D_7	$\theta_4-\theta_5$	ΔD_4	Sp	$\Delta(D_8-D_7)$	$\Delta(\Psi_4-\Psi_5)$	$\Delta(\Psi_2-\Psi_4)$ $\Delta(\Psi_5)$	Ψ_4	
	2C					4→7	D_4	D_5	$\theta_4,$ $\theta_3-\theta_5)$	$\theta_3-\theta_5$	ΔD_4	Sp	$\Delta(\Psi_4-\Psi_5)$	$\Delta(\Psi_4-\Psi_5)$	None	Ψ_4	
	2D					#4	AC	D_3	D_4	$\theta_3-\theta_2$	Sp.	S/t	$\Delta(D_7-D_4)$	$\Delta(\Psi_3-\Psi_2)$	None	Ψ_3	
	2E					#3	AC	D_2	D_3	None	Sp	$S/2_t$	$\Delta(D_4-D_3)$	None	None	Ψ_2	

Table C.6

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ϵ				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
33	1A	3^o Right	0	135^o	$D_1-D_2=+100$	Entrance $9\rightarrow10$	AC	D_8	$D_{10}-D_9$	$\theta_6-\theta_8$ $\theta_8-\theta_{10}$	Sp	None	None	None	None	Ψ_8	
	1B					#8	AC	D_6	D_8	$\theta_5,\ \theta_6$	$S/_t$	Sp	$\Delta(D_9-D_{10},\ D_8)$	$\Delta(\Psi_6-\Psi_5)$	None	$\Delta\Psi_6$	
	1C					$2\rightarrow4\rightarrow6$	D_6	D_5	$\theta_6/\theta_4,\ \theta_5$	None	$\Delta(\Psi_6-\Psi_4)$	Sp	$\Delta(\Psi_4-\Psi_6,\ \Psi_9)$	None	None	$\Delta(\Psi_6-\Psi_4)$	
	1D					#6	AC	D_4	D_6	$\theta_4-\theta_2,\ \theta_1$	$S/_t$	Sp	$\Delta(D_8,\ D_6-D_5)$	$\phi^\sim$ D_2-D_1	$\Delta(\Psi_4-\Psi_2,\ \Psi_1)$	$\Delta\Psi_4$	
	1E					#4	AC	D_2	D_4	$\theta_2,\ \theta_1$	Sp	$S/_t$	$\Delta(D_6-D_5,\ D_4)$	$\phi^\sim$ $D_2-D_1=+100$	None	$\Delta(\Psi_2-\Psi_1)$	
34	1A	7^o Left	+150	000	ϵ at 12-13 = +100	3-4	AC	D_5	D_3-D_4	$\theta_3-\theta_5-\theta_7$	Sp	$S/_t$	$\Delta(D_3-D_4)$	$\Delta(\Psi_5-\Psi_7)$	None	$\Psi_6-\Psi_{10}$ Open	11,12
	1B					$12\rightarrow10\rightarrow6$	D_6	D_5	$6\rightarrow10,\ \theta_5$	$6\rightarrow10,\ \theta_5-\theta_7$	$\Delta(\Psi_6-\Psi_{10})$	ΔD_6	$\Delta(\Psi_6-\Psi_{10})$ $\Delta\Psi_5$	$\Delta(\Psi_5-\Psi_7)$, $\Delta(\Psi_7-\Psi_9)$	None	$10\rightarrow6$	
	1C					5	AC	D_7	D_5	$\theta_5-\theta_7-\theta_9$	$\Delta(\Psi_7-\Psi_9)$	Sp	$\Delta D_3/D_5$	$\Delta(\Psi_7-\Psi_9)$	$\Delta(\Psi_9-\Psi_{11})$	$\Delta\Psi_9$	
	1D					6-7	AC	D_9	D_6-D_7	$\theta_9-\theta_{10}-\theta_{13}$	Sp	ΔD_9	$\Delta(D_6-D_7)$	$\Delta(\Psi_9-\Psi_{11})$	$\Delta(\Psi_{10}-\Psi_{11})$	$\Delta\Psi_9$, $\Delta\Psi_{11}$	
	1E					9	AC	D_{11}	D_9	$\theta_{10}-\theta_{12}$, $\theta_{11}-\theta_{13}$	Sp	ΔD_{11}	$\Delta(D_6-D_7/D_9)$	$\Delta(\Psi_{11}-\Psi_{13})$	$\Delta(\Psi_{10}-\Psi_{12})$	$\Delta\Psi_{11}$ $\Delta\Psi_{13}$	
	1F					10-11	AC	D_{13}	$D_{10}-D_{11}$	$\theta_{10}-\theta_{12}$, $\theta_{11}-\theta_{13}$	Sp	ΔD_{13}	$\Delta(D_{10}-D_{11})$	$\Delta(\Psi_{13}-\Psi_{12})$	None	$\Delta\Psi_{13}$	
	1G					12-13	AC	None	$D_{12}-D_{13}$	None	Sp	None	$\Delta(D_{10}-D_{11}/D_{12}-D_{13})$	None	None	None	

Table C.7

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ϵ				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
35	1A	7° Left	0	000	D_5+0.5 Mile =℄±50	D_1= 0.5 Mile	D_1	D_2	ϕ_5, θ_1,θ_2	θ[illegible], θ_2,θ_3	Sp	None	None	None	None	Ψ_2	
	1B					#1	AC	D_2	D_1	D_2	ΔD_5	ΔD_2	$\Delta(\phi_5-\Psi_2)$	$\Delta(\Psi_2-\Psi_3)$	None	$\Delta\Psi_2$	
	1C					2→3	AC	D_5	D_2-D_3	None	ΔD_5	Sp	$\Delta(D_1,D_2-D_3)$	$\Delta(D_2,\Psi_5)$	None	$\Delta\Psi_5$	
	1D					2→5	D_5	None	D_5,θ_5	None	Sp	None	$\Delta(D_2-D_3, \Delta\Psi_5)$	None	None	$\Delta\Psi_5$	
36	1A	7° Left	0	000	D_5+0.5 Mile=℄±50	D_1= 0.5 Mile	D_1	D_2	$\theta_1-\theta_3$, θ_2	$\theta_2-\theta_3$, θ_5	Sp	None	None	None	None	Ψ_2	
						#1	AC	D_2	D_1	D_2	ΔD_2	Sp	$\Delta(\Psi_2-\Psi_5, \Psi_3)$	None	None	$\Delta\Psi_2$	
						2→3	AC	D_5	D_2-D_3	None	ΔD_5	Sp	$\Delta(D_1, D_2-D_3)$	$\Delta(D_2,\Psi_5)$	None	$\Delta\Psi_5$	
						2→5	D_5	None	D_5,θ_5	None	Sp	None	$\Delta(D_2-D_3, \Psi_5)$	None	None	$\Delta\Psi_5$	

Table C.8

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
37	1A	7° Left	0	000	ε at 6 = ±50	Entrance	AC	D_4	D_1-D_2	$\phi_{FA}-\theta_{FB}$	Sp	None	None	None	None	ϕ	
	1B					2-4	D_4	D_5	$\phi_{FB}-\phi_{RB}$	$\theta_4-\theta_5$	Sp	ΔD_4	$\Delta(\phi_{FB}-\phi_{RB})$	$\Delta(\Psi_4-\Psi_5)$	None	$\Delta\Psi_4$	
	1C					4→5	AC	None	D_4-D_5	None	Sp	None	$\Delta(\Psi_4, \phi_{FB}-\phi_{RB})$	$\Delta(\Psi_7-\Psi_6)$	None	$\Delta\Psi_7$	
	1D					4-6	D_6	None	$\theta_6-\theta_7$	None	Sp	ΔD_6	$\Delta(\Psi_6-\Psi_7)$	None	None	$\Delta\Psi_7$	

Table C.9

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ϵ				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
38	1A	7° Left	+150'	000	ϵ at 8-9 = +100	Entrance	AC	D_4	D_1-D_2	$\theta_3-\theta_4$	Sp	None	None	None	None	None	
	1B					4→6	D_4	D_3	$\overset{4\to6}{\theta_3}$	$\theta_3-\theta_5$	$\Delta(\Psi_4-\Psi_6)$	ΔD_4	$\Delta(\Psi_4-\Psi_6)$, $\Delta\Psi_3$	$\Delta(\Psi_3-\Psi_5)$	None	4→6	
	1C					3-4	AC	D_5	D_3-D_4	θ_5	Sp	$\Delta(\theta_3-\theta_4)$	$\Delta(D_3-D_4)$, $\Delta(D_1-D_2)$	$\Delta\Psi_7$	$\Delta\Psi_5$	$\Delta\Psi_7$	
	1D					4-5	D_6	D_7	D_4-D_5	$\theta_6-\theta_7$	Sp	$\Delta(D_4-D_5)$, $\Delta(D_3-D_4)/t$	$\Delta\Psi_7$	$\Delta\Psi_6$	$\Delta\Psi_9$	$\Delta\Psi_7$	
	1E					5-6	D_6	D_7	D_5-D_6	θ_7	Sp	$\Delta(D_5-D_6)$ $(D_4-D_5)/t$	$\Delta\Psi_7$	$\Delta\Psi_9$	$\Delta\Psi_8$	$\Delta\Psi_7$	
	1F					6-7	AC	D_9	D_6-D_7	$\theta_8-\theta_9$	Sp	$\Delta(D_6-D_7)$ $(D_5-D_6)/t$	$\Delta\Psi_9$	$\Delta\Psi_8$	None	$\Delta\Psi_9$	

Table C.10

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
39	1A	3° Right	+100	120	D_2= +150' to $\omega/2$	10	AC	D_9	D_{10}	$\theta_8-\theta_9$	Sp	None	None	None	None	None	
						9	AC	D_8	D_9	$\theta_7-\theta_8$	Sp	ΔD_8	$\Delta(\Psi_5-\Psi_8)$	$\Delta(\Psi_7-\Psi_8)$	$\Delta(\Psi_4-\Psi_8)$	$\Delta\Psi_8$	
						8→4	D_8	None	$\theta_4-\theta_8$, θ_5	None	Sp	ΔD_8	$\Delta(\Psi_4-\Psi_8)$	$\Delta(\Psi_8-\Psi_5)$	None	$\Delta(\Psi_4-\Psi_8)$	
						8	AC	D_4	D_8	$\theta_4-\theta_5$	Sp	S/t	$\Delta(\Psi_4-\Psi_5)$	$\Delta(\Psi_3-\Psi_4)$	None	$\Delta\Psi_4$	
						4→2	D_4	None	$\theta_4-\theta_2$, θ_3	None	$\Delta(\Psi_4-\Psi_2)$	Sp	$\Delta(\Psi_4-\Psi_2)$	$\Delta\Psi_3$	None	$\Delta(\Psi_4-\Psi_2)$	
						4	AC	D_3	D_4	$\theta_3-\theta_2$	Sp	ΔD_3	$\Delta(\Psi_3-\Psi_2)$	None	None	$\Delta\Psi_2$	
						3	AC	D_2	D_3	None	Sp	$S/2/t$	$\Delta\Psi_2$	$\Delta D_4/D_3$	None	$\Delta\Psi_2$	

Table C.11

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
40	1A	3^o Right	0	120	D_2=+150 to $\omega/2$	Entrance 9-10	AC	None	D_9-D_{10}	$\theta_7-\theta_8$	Sp	None	None	None	None	Ψ_8	
	1B					8→6→4	8→6	D_8	$\theta_8-\theta_6$, θ_3	$\theta_8-\theta_5$, θ_6	ΔD_8	Sp	$\Delta(\Psi_8-\Psi_6, \Psi_3)$	$\Delta(\Psi_8-\Psi_7, \Psi_5)$	None	$\Delta(\Psi_8-\Psi_6)$	
	1C					7-8	AC	None	D_7-D_8	$\theta_6-\theta_5$, θ_4	ΔD_6	ΔD_5	$\Delta(D_9-D_{10}, D_7-D_8)$	$\Delta(\Psi_4-\Psi_6, \Psi_3)$	None	$\Delta\Psi_3$	
	1D					#6	AC	None	D_6-D_5	$\theta_3-\theta_4$	ΔD_4	ΔD_3	$\Delta(D_7-D_8, D_6)$	$\Delta(\Psi_3-\Psi_4)$	$\Delta(\Psi_4-\Psi_2)$	$\Delta\Psi_4$	
	1E					#4	AC	None	D_4	$\theta_2-\theta_1$	Sp	ΔD_2	$\Delta(D_6-D_4)$	$\Delta(\Psi_1-\Psi_2)$	None	$\Delta\Psi_1$	
	1F					2-4	D_2	None	$\theta_2-\theta_1$	None	Sp	ΔD_2	$\Delta(D_4, \Psi_2-\Psi_1)$	None	None	$\Delta\Psi_2$	

Table C.12

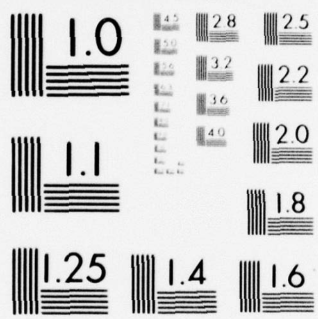
Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
41	1A	3^o Right	0	120	D_2=+150 to $\omega/2$	Entrance #12	AC	None	D_{12}	None	Sp	None	None	None	None	Ψ_{10}	13
	1B					#11	AC	None	D_{11}	None	Sp	None	$\Delta(\Psi_{11},\Psi_{10},\Psi_9)$	None	None	$\Delta\Psi_{10}$	
	1C					10→8→6	AC	None	$\theta_{10}-\theta_8$, θ_9	None	ΔD_{10}	None	$\Delta(\Psi_{10}-\Psi_8$, $\Psi_5)$	None	None	$\Delta(\Psi_{10}-\Psi_8)$	
	1D					#10	AC	None	D_{10}	None	ΔD_8	None	$\Delta(\Psi_8-\Psi_6$, $\Psi_5)$	None	None	$\Delta(\Psi_8-\Psi_5)$	
	1E					#8	AC	None	D_8	None	$SI/_{Nt}$	None	$\Delta(\Psi_6-\Psi_4$, $\Psi_5)$	None	None	$\Delta\Psi_4$	
	1F					#6	AC	None	D_6	None	$SI/_{Nt}$	None	$\Delta(\Psi_4-\Psi_3)$	None	None	$\Delta(\Psi_4-\Psi_2)$	
	1G					#4	AC	None	D_4	None	$SI/_{Nt}$	None	$\Delta(\Psi_3-\Psi_2)$	None	None	$\Delta\Psi_3$	
	1H					#3	AC	None	D_3	None	Sp	None	$\Delta\Psi_2$	None	None	$\Delta\Psi_2$	

Table C.13

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
29R	1A	7° Left	+100	000	Passing	$D_v=7L$	D_v				ΔD_v	None	$\Delta(\Psi_v-\Psi_{Rc})$	None	None	$D_v=3L$	14
	1B					$D_v=5L$	D_v				ΔD_v	None	$\Delta(\Psi_v-\Psi_{Rc})$	None	None	$D_v=3L$	
	1C					$D_v=3L$	D_v				ΔD_v	None	$\Delta(\Psi_v-\Psi_{Rc})$	$\Delta\alpha_v$	None	$D_v=3L$	
	1D					$D_v=2L$	D_v		D_R		ΔD_v	None	$\Delta(\Psi_v-\Psi_{Rc})$	$\Delta\alpha_v$	None	$\Delta\Psi_v$	
	1E					$D_v=0$	0		D_v-D_R		ΔD_v	ΔD_{Rc}	$\Delta(\Psi_{Rc}-\Psi_{Rs})$	$\Delta(\Psi_{Rc}-\Psi_{Bc})$	None	$\Delta(\Psi_{Rc}-\Psi_{Rs})$	
	1F					$D_v=-2L$											14

AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)
MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A
UNCLASSIFIED USCG-D-38-78 NL

5 OF 6
AD
A059891



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table C.14

Figure #	Transit	Entrance Condition		Heading	Intention	Location	Long. Posit. Measurement		Lateral Position Measurement		Long. rate Measurement		Lateral rate measurement			Turn Indication	Notes
		γ	ε				Pri.	Sec.	Primary	Secondary	Pri.	Sec.	Primary	Sec. 1	Sec. 2		
41	2A	3^o Right	O	120	D_2=+150 to $\omega/2$	Entrance #12	AC	None	D_{12}	None	Sp	None	None	None	None	Ψ_{10}	
	2B					#11	AC	None	D_{11} '	None	Sp	None	$\Delta(D_{12}-D_{11})$	None	None	$\Delta\Psi_{10}$	13
	2C					10→8→6	AC	None	$\theta_{10}-\theta_8$, θ_9	None	ΔD_{10}	None	$\Delta(\Psi_{10}-\Psi_8, \Psi_5)$	None	None	$\Delta(\Psi_{10}-\Psi_8)$	
	2D					#10	AC	None	D_{10}	None	ΔD_8	None	$\Delta(D_{11}-D_{10})$	None	None	$\Delta(\Psi_8-\Psi_5)$	
	2E					#8	AC	None	D_8	None	SI/Nt	None	$\Delta(D_{10}-D_8)$	None	None	$\Delta\Psi_4$	
	2F					#6	AC	None	D_6	None	SI/Nt	None	$\Delta(D_8-D_6)$	None	None	$\Delta(\Psi_4-\Psi_2)$	
	2G					#4	AC	None	D_4	None	SI/N_t	None	$\Delta(D_6-D_4)$	None	None	$\Delta\Psi_3$	

C.3.4 Summary

The objective of presenting the information in this section of the appendix has been to illustrate the configuration format and information selection as it is accomplished by the PON model. The information is, of course, static and represents an instantaneous situation. The method of approach, however, was invaluable in the development of the dynamic PON model.

C.4 EXPLANATORY NOTES

(1) The vessel has entered with no crab angle and will begin an immediate set to the right. He will see ϕ_C - ϕ_S opening rather rapidly, and take corrective action to return to ℄. When on or very near ℄, he will adjust the course in gradual increments of 1° to maintain desired track.

(2) Entrance is with 7° left crab, anticipating set. He wishes to be 150 feet off the centerline, with a tolerance of 50 feet to the left of this track and 100 feet to right, with a situation where he expects to encounter small vessels which do not require him to make a passing maneuver, but does allow sufficient room for smaller vessels to use the left side of the channel. ϕ_C and ϕ_S will be observed resulting in a correction action.

(3) Same situation as (2), except mariner uses ship's head and front range angle as primary guidance information. ψ_C and ψ_S are the angles between ship's head and the nearest aid (front marker, R_f) and farthest aid (R_r).

(4) Proceeding from the entrances at #2 to #4, the mariner will adjust for set by coming left until a crab angle is established which will permit him to maintain intended track. The process repeats to the end of the channel. The lateral position measurement θ_4 - θ_6 - θ_8 means he is comparing the differences in angle sets to these numbered aids.

(5),(6) After establishing crab angle, the mariner picks a point ahead based on an estimate of the distance off the farthest visible aid. This is designated as D_{10}, but

will be limited by detectable range. Based upon this imaginary point ahead, he will estimate the angle from this point to the vessel and base course changes on the angle change. His secondary estimate is the angle from ship's head to the point.

(7) This is a downbound transit where the vessel desires to be closer to the aids. The PON is the same as Figure C.27, steps 1A through 1C.

(8) A downbound transit where the vessel enters 50 feet from ℄, closer to the aids and the PON is the same as Figure C.27, steps 2A through 2C.

(9) In Figure C.28, SA>2S, SA<5S. This is a combination of cocked gates, pairs, and single side aids, depending upon the detection range. For this transit, assume that both aids on the red side are visible when the vessel is at the entrance.

(10) Under lateral rate measurements, $\Delta\phi \approx D_3 - D_4$ means that the mariner is observing an angle change to a point on the line which joins aids 3 and 4. This point is on his desired track, in this case, 150' to the right of ℄.

(11) Depending upon the channel width, the turn will be initiated at or before 4→6. For a narrow channel, with $B = 45°$, the LOP 4→6 is located too late for turn initiation due to vessel advance.

(12) The entrance is the same as Figure C.31, 1A, and assumes the crab angle has been established prior to 3-4.

(13) For Figure C.41, two transits are implied. Transit 1A through 1H uses only angular measurements, and 2A through 2C uses primarily distance measurements. The accuracy achieved under these two different conditions may indicate the sensitivity differences.

(14) The R designation next to the figure number indicates a restriction. In this case, another vessel is approaching at the same speed as own vessel. The entrance times of both vessels will be the same. Therefore, depending upon the spacing of aids, the passing can occur abeam of an aid, or anywhere between aids. Figure C.25 shows the general passing condition and symbology to be used. The longitudinal and lateral position measurement of own vessel is accomplished in the same manner as for the straight channel. The rate and guidance measurements are with respect to the approaching vessel and the

aids to navigation system. Locations are designated in own ship-lengths apart from other vessels, e.g., $D_V = 7L$. After $D_V = 0$, the situation becomes the same as the standard configuration.

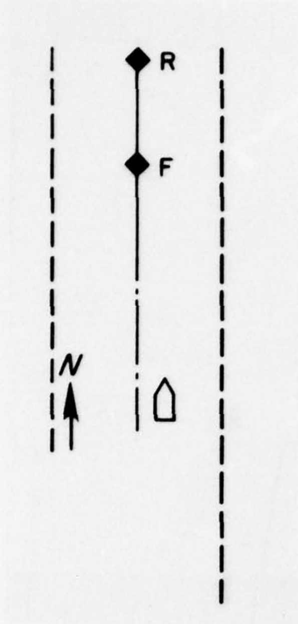


Figure C.26

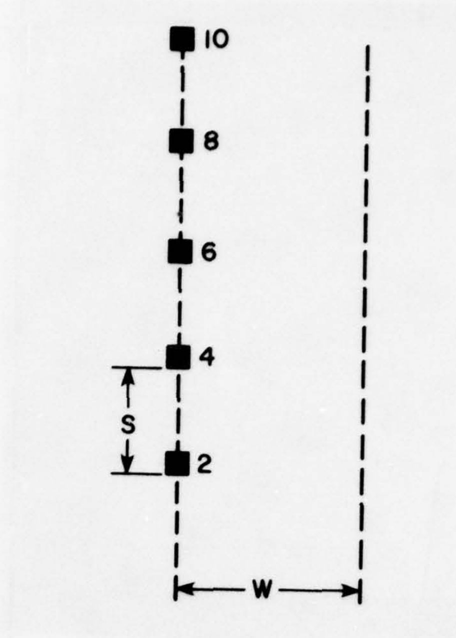


Figure C.27

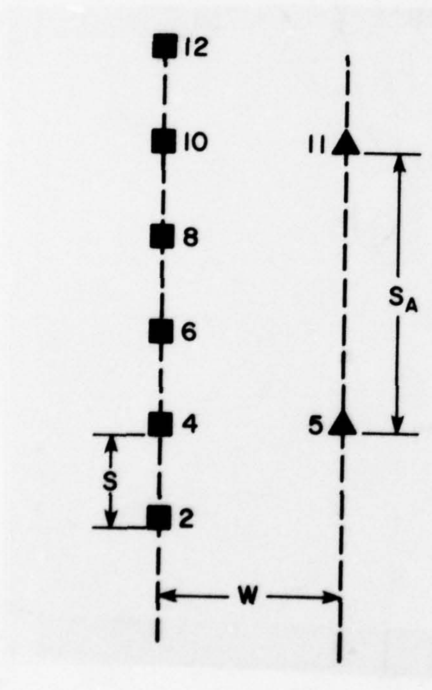


Figure C.28

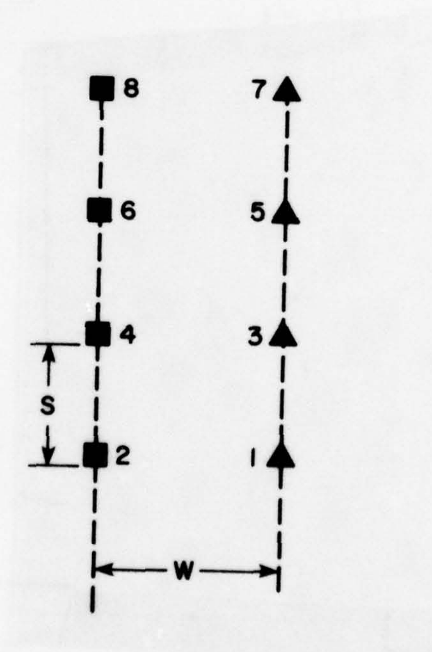


Figure C.29

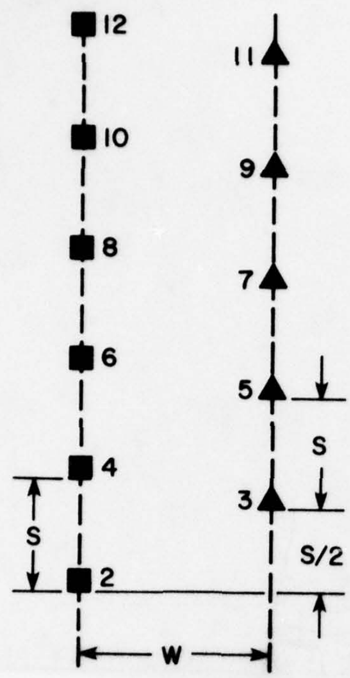


Figure C.30

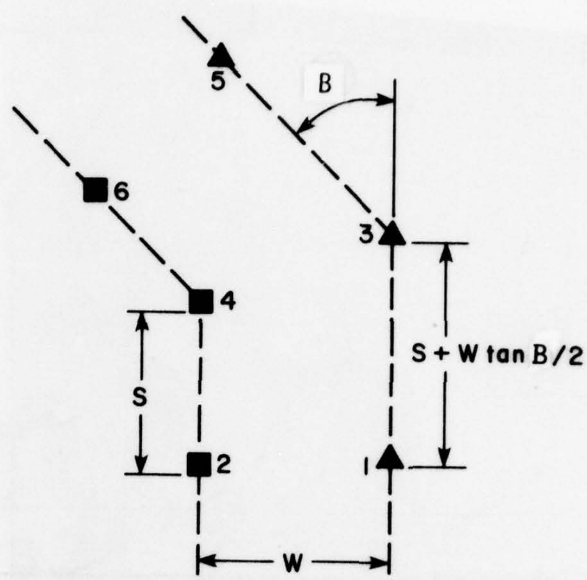


Figure C.31

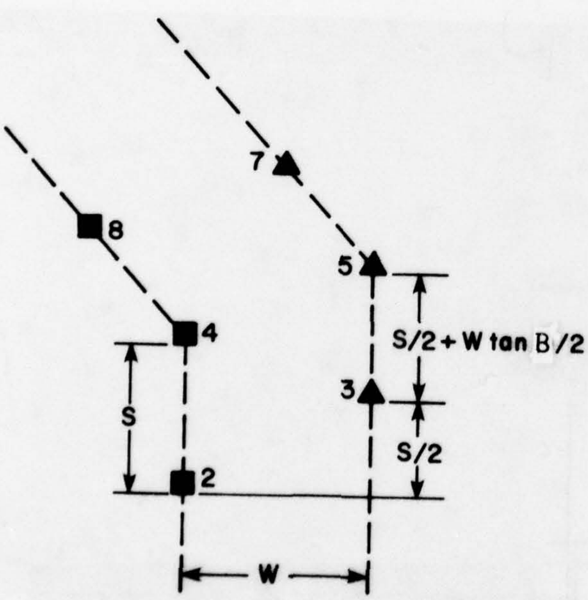


Figure C.32

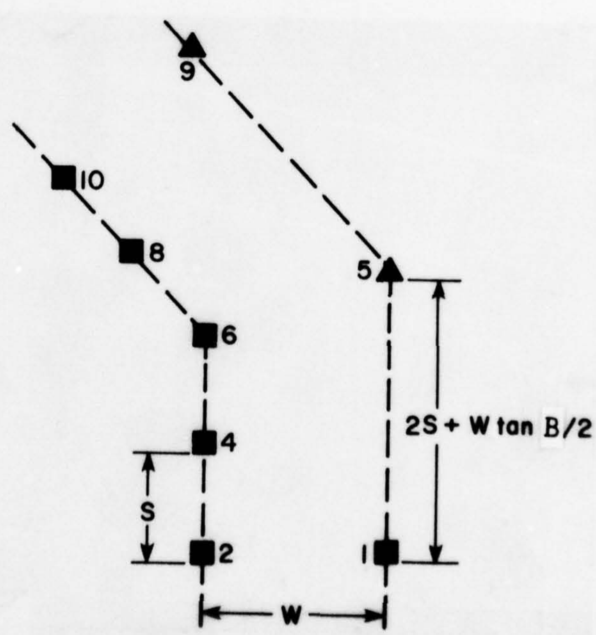


Figure C.33

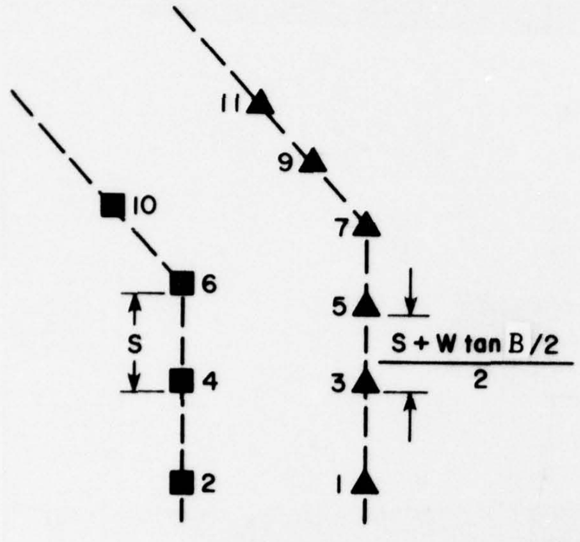


Figure C.34

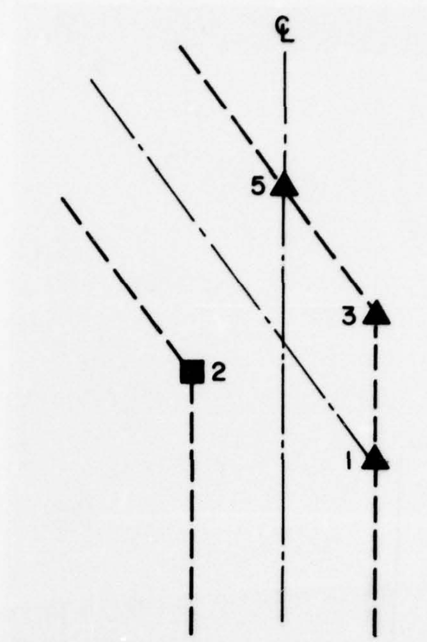


Figure C.35

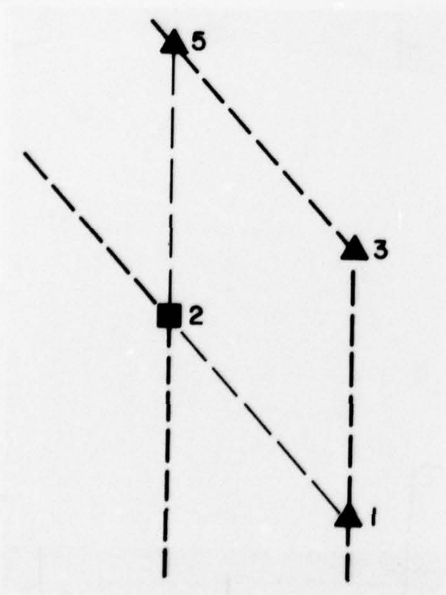


Figure C.36

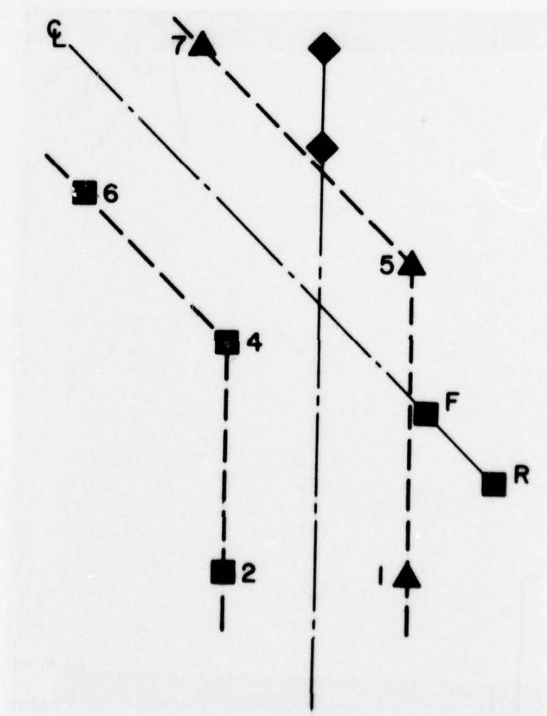


Figure C.37

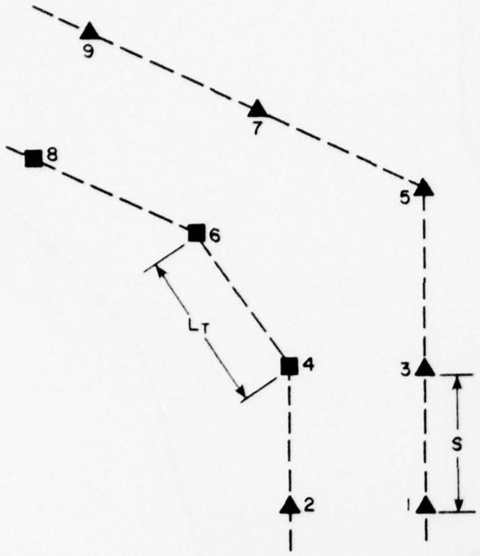


Figure C.38

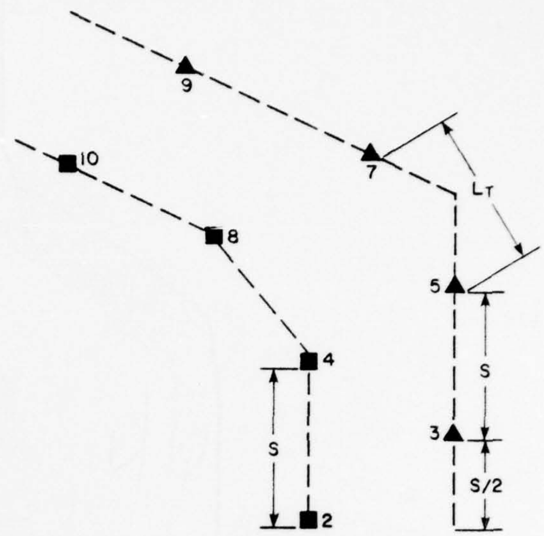


Figure C.39

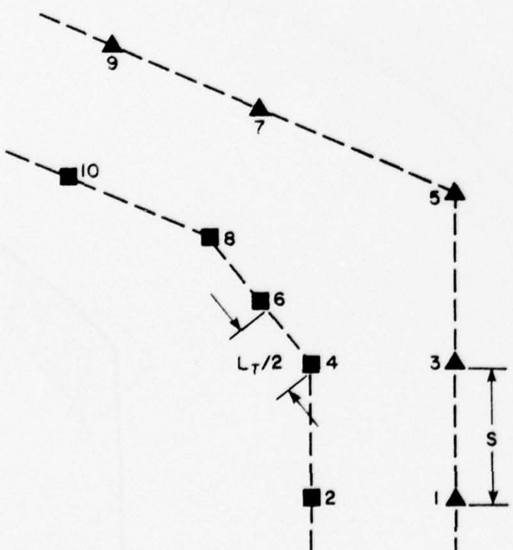


Figure C.40

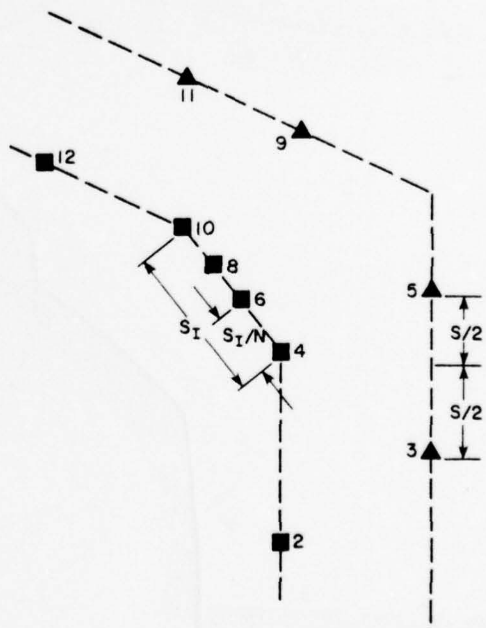


Figure C.41

APPENDIX D

COMMERCIAL VESSEL ACCIDENTS

D.1 INTRODUCTION

A small sample of commercial vessel casualties was examined to determine whether or not aids to navigation could be considered as being related to the casualty. The examination was not specifically directed towards the concept that an aid insufficiency caused the incident to occur, e.g. a vessel grounded due to a buoy being off station or a beacon extinguished. The data review was primarily oriented towards the mariner, and his ability to judge or misjudge a situation where aids were used for navigation. The results of the casualty data examination would hopefully reveal patterns of where accidents occurred, whether the mariner misjudged vessel location using aids, or whether other misjudgments contributed to the casualty. A summary of these data appears in Section 3.1.2 of the basic report.

D.2 DATA SELECTION METHOD

The Information and Analysis Staff (GMA) of the Coast Guard Office of Merchant Marine Safety was requested to provide a computer printout of selected vessel casualties. The printout selection was based upon the following; with the coding instructions given in parenthesis:

(1) Only vessel groundings were to be called out. (Col 32, 33, code 21 and 22)

(2) The areas were New York, Delaware Bay, Chesapeake Bay, and Texas. (Col 45-47; Grid Locators 113, 114, 115, 117, 131)

(3) Vessels under 300 Gross Tons were not included. (Col 26, all except 1-3)

(4) Operators did not include pleasure boats, harbor workers, and cause factors eliminated equipment or structural failures. (Col 34; various codes)

(5) The printout was for 1971 through 1976. Using these criteria, 314 cases were printed out of the computer stored data.

A preliminary review of the actual Marine Investigation Officers report, on microfilm, revealed that additional selectivity was necessary. Many casualties (anchors dragging, adrift barges, etc.) would not be related to the use of the aids to navigation system. To provide this additional selectivity, a manual screening of the printout was done to identify only those accident causes which involved operator misjudgments (Column 35). This reduced the number of cases to be reviewed from 314 to 137. A further reduction became necessary because the 1971 cases had not been transferred to microfilm and the latter portion of 1976 had not been microfilm processed. Thus, the total number of cases available for review was reduced to 106.

D.3 DATA PRESENTATION

Table D.1 summarizes the results of the examination of the individual cases. After identification by case number, the following topics have been selected from the total computer printout, since they may influence future aids to navigation concepts.

(1) Vessel length. May be a function of maneuverability, etc.

(2) Age. Indications are that the older the vessel, the poorer its maneuvering characteristics. The age factor is related to the year of the accident which is identified by the first digit of the case number. Thus a vessel indicated as being less than 5 years old having an accident in case 20133 (1972) would be at least 5 years old at the present time.

Table D.1

Summary of Commercial Vessel
Casualty Cases Addressed

Case	Length	Age	Time	Vis	Harbor Element	Moving Traffic	Current or Wind	A/N	NOTES
32757	5-600	15-20	N	C	Bend	No	Yes	No	Rounding buoy #6, Sabine Bank. After turn, vessel sheered.
22049	5-600	20-25	N	C	Bend	No	No	No	At buoy #6, Sabine River, Crowded channel edge in 200 ft. channel
21489	>700	0-5	D	C	Bend	No	No	No	At buoy #6, Sabine River, crowded western edge.
52900	5-600	5-10	N	C	Straight	No	No	Yes	Charted shoal not marked by aid. O in C recommended buoy relocations. Sabine.
20211	6-700	10-15	D	C	Bend	No	No	Yes	Near Sabine Bank buoy #6, favored eastern edge of channel due to dredging. Did not allow for advance and transfer. No buoys on west bank.
60897	6-700	25-30	N	C	Bend	No	Yes	No	La Quinta Channel, turned right at #36 out of main ship channel. Unlisted aid.
61036	>700	10-15	N	C	Straight	No	Yes	No	When changing pilots in Galveston Channel into Bolivar Road at buoy 14, strong ebb current.
60836	6-700	25-30	N	C	Straight	Yes	No	No	Grounded while passing, Texas City Channel.

Table D.1 (Continued)

Case	Length	Age	Time	Vis	Harbor Element	Moving Traffic	Current or Wind	A/N	NOTES
51049	1-200	5-10	N	C	Straight	Yes	No	No	Hudson River. Maneuvering to avoid downbound tug/tow near New Hamburg.
41638	2-300	25-30	D	C	Bend	No	Yes	No	Grass Hassock Channel N.J. Pounding buoy #23, aground off Motts Point.
41733	1-200	15-20	N	C	Bend	No	Yes	No	Wards Point N.Y. between buoys 54 & 56, outbound
41876	2-300	0-5	D	R	Bend	No	Yes	No	Tug w barge in Hell Gate N.Y.
41039	1-200	25-30	D	C	Bend	No	No	No	Fishing vessel grounded after bend at Montauk Point.
41038	6-700	15-20	N	C	Anchorage	Yes	No	No	Gravesend Anchorage N.Y. Maneuvering to avoid vessel entering anchorage
41497	2-300	15-20	D	C	Straight	Yes	No	No	Passing
42418	2-300	15-20	D	C	Bend	No	No	No	Coney Is. Channel, near buoy #3
31905	5-600	15-20	N	C	Straight	No	Yes	No	Hackensack River N.J. Marion Reach, just prior to bend. Tugs assisting
50517	6-700	20-25	N	C	Bend	No	Yes	No	Bergen Pt. N.Y. with tugs outbound. Swung too wide
41903	>700	0	D	F	Entrance	Yes	?	No	Heavy traffic, radio confusion
20389	5-600	0-5	N	C	Bend	No	Yes	No	Turning into east side of C & O canal. 2 knot ebb.
51177	2-300	25-30	N	C	Bend	No	Yes	No	Del. River, Bulkhead Bar Range to New Castle Range. Did not all set and drift.
21132	5-600	20-25	N	C	Bend	No	No	No	Turning from Bulkhead Channel into New Castle Channel, Delaware R. Swung too far right
20964	>700	10-15	D	F	Straight	No	No	No?	Delaware River, New Castle Range, ½ mile above buoy 2N.
30689	3-400	0-5	N	C	Straight	No	Yes	No	Tug and tow at 250'. Wind and tide took tow to N side of channel. Sandy Hook
21206	>700	0-5	D	R	Entrance	No	No	Yes	Delaware River. Vis ½ mile in rain. Misidentified buoys? Nav. by radar alone.
42593	6-700	0-5	T	C	Straight	Yes	No	No	Passing
50821	2-300	0-5	N	C	Entrance	No	No	Yes	Sabine Pass Approach. Misidentified East Jetty light and several other aids.
20336	6-700	5-10	D	C	Bend	No	Yes	No	Near Buoy #6, Sabine Bank Approach, vessel set to port by current when changing from 134° to 180°
50735	6-700	25-30	N	C	Bend	No	No	No	Too wide of a turn at bend in Calcasieu River, TX.
42438	>700	15-20	N	C	Bend	No	Yes	Yes	At bend, Sabine Bank Channel buoys #4&5. Buoys in clutter. Light extinguished.
53038	6-700	20-25	D	C	Junction	Yes	Yes	No	Slowed for ICW traffic, in Houston Ship Canal. Strong flood tide.
21580	>700	0-5	N	C	Bend	No	No	No	Exiting Sabine Pass, made too wide of turn when outbound.

Table D.1 (Continued)

Case	Length	Age	Time	Vis	Harbor Element	Moving Traffic	Current or Wind	A/N	NOTES
41655	6-700	20-25	T	F	Bend	No	Yes	No	From La Quinta Channel, turned too wide into Corpus Christi Channel.
51143	5-600	25-30	D	C	Bend	Yes	No	No	Too wide of a turn in traffic
52040	>700	0-5	N	F	Straight	Yes	Yes	No	Golveston Bay, Bolivar Roads between 7 A and 9, while passing
21097	6-700	10-15	D	C	Bend	No	Yes	No	Grounded while in slight bend after discharging pilot. Buoy off station into channel.
20833	6-700	0-5	T	C	Straight	No	Yes	No	Texas City Channel. Favored N side of channel N wind, 5-6 kn. Overcompensated
42013	>700	0-5	D	F	Bend	No	Yes	Yes	Sabine Bank Channel. #15 buoy missing. Grounded after turn while attempting to align.
40754	6-700	20-25	D	C	Entrance	No	No	No	Maneuvering to pick up pilot at sea buoy.
31822	6-700	20-25	D	C	Bend	No	Yes	No	Texas City Channel 90° bend, with tugs.
51707	5-600	5-10	N	C	Straight	No	Yes	Yes	Buoy off station, Range light out. Sabine River Channel
20959	5-600	5-10	N	C	Bend	No	No	Yes	Could not see unlighted aids on stbd side of bend.
31120	5-600	25-30	N	C	Straight	No	Yes	No	Pushing tow, Houston Ship Canal. Wind caught bow.
30774	>700	10-15	N	C	Straight	Yes	No	No	Passing in Texas City Channel.
60123	5-600	25-30	D	C	Straight	Yes	No	No	Passing
60438	2-300	20-25	D	C	Straight	No	Yes	No	Chesapeake Bay, Indian Creek Daybeacon #8. Wind 15-20 knots.
60554	>700	20-25	N	C	Entrance	No	No	Yes	Entering Del. Bay. Turned on wrong Buoy (FB) instead of (DC)
60557	6-700	15-20	N	F	Straight	Yes	No	No	Delaware river, Steering on right bank to avoid traffic.
61400	2-300	25-30	N	C	Obstruct	No	Yes	No	40-50 knot winds, vessel drifted
61511	>700	5-10	D	C	Bend	No	Yes	No	La Quinta Channel. Outbound from Corpus Christi. Turned too wide at junction buoy
62343	>700	0-5	T	C	Entrance	No	No	No	Misjudged approach zone in Panama Canal.
62395	6-700	5-10	N	C	Straight	No	Yes	No	Beam wind in Houston Ship Canal. Misjudged effect
62600	6-700	10-15	N	C	Anchorage	No	No	No	Pilot disreguarded aids, Thomas Point. Aground at full speed after relieved by master.
62738	>700	15-20	D	R	Straight	No	Yes	No	Heavy squall blocked radar. Wind effect caused agrounding.
63353	>700	0-5	D	C	Bend	No	Yes	No	Bergen Point. Outbound Port Eliz to sea. Made too wide of turn
63388	6-700	25-30	N	C	Anchorage	No	No	No	Draft 26, depth 25 in Panama Canal Anchorage
63389	4-500	5-10	N	C	Straight	No	Yes	No	Houston Ship Canal. Beam wind.
62877	6-700	510	T	R	Entrance	No	No	Yes	Misidentified buoy at entrance to Delaware Bay, 2TS instead of IHB F.
60026	5-600	0-5	N	C	Bend	No	No	Yes	Buoy lights caused confusion. (white and green) Sabine Channel.

Table D.1 (Concluded)

Case	Length	Age	Time	Vis	Harbor Element	Moving Traffic	Current or Wind	A/N	NOTES
52882	5-600	0-5	D	F	Bend	No	No	No	Radar navigating Ambrose channel. Turn at Buoy 13. Too wide of turn
41845	6-700	10-15	D	C	Bend	No	Yes	No	Hell Gate N.Y. 3 tugs assisting. 3 knot ebb current.
51664	5-600	0-5	N	C	Bend	No	No	No	Poor vessel maneuvering characteristics, made too wide of turn
30267	>700	0-5	D	C	Bend	No	No	No	Entering Raritan East Reach from Chapel Hill. Misjudged vessel turning radius.
32080	6-700	15-20	N	F	Bend	No	Yes	No	Operator could not estimate when to turn using radar only.
42823	6-77	5-10	T	C	Straight	Yes	Yes	No	Maneuvering to avoid unidentified traffic in Shooters Is. Reach, Newark. Grounded at Bergen Pt.
20987	6-700	10-15	N	C	Anchorage	No	Yes	No	Maneuvering out of anchorage. Misjudged vessel location
20271	5-600	10-15	D	C	Bend	No	Yes	No	Maneuvering from Hudson River into Kingston Channel (400'wide) Flood current
41587	5-600	15-20	D	C	Bend	No	Yes	No	Hell Gate, NY 1 hour after high water slack
21411	6-700	0-5	D	C	Straight	Yes	?	No	Attempting to pass, no answer from other vessel, slowed, grounded
30010	6-700	15-20	T	C	Straight	No	Yes	No	Entering Chapel Hill from Ambrose, NY, Wind at 20 knots. Grounded east bank.
42765	6-700	25-30	D	C	Bend	No	Yes	No	Entering Arthur Kill from Const Hook Range NY. Tugs in assistance
20783	>700	10-15	D	C	Entrance	Yes	No	No	Maneuvering to avoid another vessel near pilot station
21367	5-600	5-10	N	I	Bend	No	Yes	Yes	Aids covered with ice, missing in Chesapeake Bay. Grounded #12 buoy Huntinfield Point
51192	2-300	20-25	T	C	Bend	No	No	No	Changing Pilots, Balto. Ferry Bar Channel. Vessel slowed, drifted aground as turning
42300	6-700	15-20	N	C	Bend	No	Yes	No	Entrance C & O canal. Winds 11-21 knots gusting.
31464	5-600	20-25	D	F	Straight	Yes	No	No	Excess speed in fog. Began to slow for vessel 2 miles ahead. Grounded inside 18,C, Chesapeake Bay Craghill Channel
21064	5-600	10-15	N	C	Straight	Yes	No	No	Maneuvering to avoid overtaking vessel, Smith Point, Chesapeake.
41618	6-700	25-30	D	C	Entrance	No	No	Yes	Misident buoy at Cape Henlopen.
21473	6-700	0-5	D	C	Entrance	No	No	No	Grounded while picking up pilot. Del Bay.
30249	>700	0-5	N	C	Bend	No	No	No	Proceeding at dead slow due to moored vessels at dock. Lost maneuvering. Cline Point
21418	5-600	5-10	D	C	Anchorage	No	Yes	No	Maneuvering in anchorage.
31938	>700	0-5	N	C	Bend	No	Yes	No	Rounding Cline Point at slow. Corpus Christi Channel.
32538	6-700	20-25	N	C	Bend	No	Yes	No	Rounding bend, La Quinta Channel at Inner Range front light. Corpus Christi

(3) Time. The general classification of time is day, night, or twilight (D, N, T).

(4) Visibility (Vis) is classified as either clear, fog, rain, or ice (C, F, R, I).

(5) Harbor modules. The area where the accident occured is described as one of the possible model parameters such as

1. Straight
2. Bend
3. Anchorage
4. Entrance
5. Isolated Obstruction
6. Bridge

(6) Traffic. If the casualty was in the presence of other moving traffic, a "yes" is indicated.

(7) Current or wind. If operator misjudgment was caused or influenced by current or wind, a "yes" is indicated.

(8) Aid to Navigation. If the casualty report specifically states that the operator judgment was influenced by an aid, a "yes" is indicated, with further explanation in the notes.

Only 83 cases are included in Table D.1. When the cases were tabulated additional exclusions were found due to possible mis-codings (anchor dragging), draft exceeding normal channel depth, and a large number of dockings and undockings in restricted areas.

D.4 DATA ANALYSIS

Because of the small sample size, no in-depth analysis or conclusions are available based on the data. Hence the analysis will be brief, and reviewed to identify any relationship to aid to navigation configurations or use.

D.4.1 Harbor Modules

The following describes the number of cases by harbor module.

Table D.2 Harbor Modules

Module	Bend	Straight	Entrance	Anchorage	Other	Total
# Cases	41	25	10	5	2	83

The two cases listed as "other" include one maneuvering at a junction to avoid crossing traffic, and one vessel grounding near a point of land in 40 to 50 knots of wind.

D.4.2 Anchorages

Of the 5 cases involving grounding while maneuvering in an anchorage, only one case was related to another moving vessel entering the same anchorage. The remaining four cases involved maneuvering at the limits of the anchorage. In no case was the presence of another vessel at anchor mentioned. As would be expected, all cases were for larger vessels, in 6 to 700 foot category, and in the mid- to older-age groupings, 10 to 25 years.

D.4.3 Entrances

Two cause factors appear prevelant at harbor entrances. These include three cases where grounding occurred when manuevering or waiting to pick up a pilot, and six cases of misidentification of aids. The greatest area of confusion appears to be the entrance to Delaware Bay, where 4 of the 6 misidentifications took place. Only one grounding casualty resulted from traffic congestion and maneuvers to avoid potential collisions.

D.4.4 Straight Channels

Of the 25 groundings in straight channels, 12 occurred in areas where no other moving traffic was in the immediate vicinity. In 9 of these 12 cases, heavy winds or currents were considered major factors in the incident. In one case, navigation was by radar in fog, another involved an unmarked shoal, and the final case was related to a dead slow condition with mild set during a pilot change.

Of the remaining 13 straight channel incidents involving other vessels in the vicinity, all were passing situations, three while in fog.

D.4.5 Bends

As indicated in paragraph D.4.1, nearly 50% of the listed grounding incidents occurred at bends in channels. Table D.3 shows the incidents in several categories.

Table D.3 Bends, General

	Visibility F or R	Time D N T	Traffic	Wind or Current	A/N	Bends, Total
Quantity	5	20,19,2	1	24	5	41

As indicated above, there is very little difference in accident occurence between day and night, and traffic had a negligible impact. Aids to navigation were specifically cited in 5 cases, including one case in the Chesapeake where aids were either covered with ice or buried in radar clutter, another two where aids were missing, and two involving lights. In the latter group, one operator unfamiliar with an area became confused with whites and greens, and one case involved an extinguished aid.

The age category for bend incidents is shown in Table D.4.

Table D.4 Age Groups, Bends

Age	0-5	5-10	10-15	15-20	20-25	25-30
Cases	12	4	4	7	7	7

In the interview phase of the program, many persons expressed the opinion that the newer vessels were generally more maneuverable, despite an increase in size. Table D.4 seems to indicate that this may not be completely accurate. As a check, the 12 vessels in the 0-5 age group were reviewed for their size. Seven were greater than 700 feet, three were from 500 to 600 feet, one was less than 300 feet, and one was between 600 and 700 feet long.

D.5 MISCELLANEOUS

Table D.5 outlines a variety of summaries from the attached data sheets.

Table D.5 General Summaries

Time D N T	Visibility C F R I	Traffic Yes No	Wind/Current Yes No	A/N Yes No
35,41,7	70,8, 4, 1	17 66	42 41	13 70

By age group, the vessels are shown in Table D.6.

Table D.6 Age Groups

Age	0-5	5-10	10-15	15-20	20-25	25-30
Straight	5	6	3	5	3	3
Bend	12	4	4	7	7	7
Other	5	2	3	1	3	3
Total	22	12	10	13	13	13

According to vessel size, the total per category is shown in Table D.7.

Table D.7 Vessel Lengths

Length	>700	6-700	5-600	<500
Number	19	30	20	14

D.6 CONCLUSIONS

The only conclusions which can be reached in the small sample size of accidents reviewed are those which point out areas where additional study or experiments are necessary. Many of the conclusions are well known, or have been substantiated by interviews, meetings, etc. For example, fog is known to have a relatively low impact on groundings because of its low incidence. Despite these limitations, the following broad concepts are presented.

(1) Navigation at bends is a primary area of concern. There is a need to examine the methods employed in the aids to navigation system to ascertain if there is sufficient information available to the mariner enabling him to properly judge the movement of the vessel. "Too wide of a turn" is a term which frequently appears in the casualty case review.

(2) The differences in day versus night are not highly significant. This supports the statements by most mariners that unlighted aids in major shipping channels may be a hazard or at least not contributory to navigation safety.

(3) Vessel maneuverability is significant. Maneuverability and size may be interactive, i.e. a large maneuverable vessel may have the similar process of navigation problems as a smaller but less maneuverable vessel.

(4) Although anchorages do not appear relatively high on the incidence list, there is some indication of a potential need for better marking of anchorage limits.

(5) The incident rate for junctions is negligible in this limited analysis. Thus, despite the requirement for increased caution and collision avoidance maneuvering, aids to navigation do not appear as a significant element at junctions.

(6) The misidentification of aids at entrances can be directly related to an experience factor. All cases occurred when no pilot was on board. This may indicate a need for better differentiation of entrance aids, since all of the cases involved entrances from sea rather than a channel entrance once inside a bay or harbor.

APPENDIX E

PREVIOUS RESEARCH VALIDATION EFFORTS IN HUMAN OPERATOR TECHNOLOGY

Previous human operator model technologies have focused on manual control tasks such as pilot models for air-to-air combat [7], tracking performance in manual anti-aircraft-artillery weapon systems [8] and pilot modeling for a remotely piloted vehicle (RPV) [9]. Previous research that is directly analogous to the current study concerns driver steering control models.

Automobile driving consists of a hierarchy of "navigation", "guidance", and "control" phases conducted simultaneously with visual search, recognition, and monitoring operations. (These terms are synonymous with estimation, decision and command/control respectively.) Navigation deals with the overall selection of a route. Guidance, in this context, is concerned with more specific questions of path details and judgements, based on a specific situation. This is made up of the selection, decision and path definition aspects of one task. If, for example, overtaking and passing were the task, guidance would include the decision to overtake and pass and the selection of the desired trajectory based on oncoming traffic and other roadway constraints. Control is the process of effecting the guidance desired by actuating the steering wheel, accelerator, and brakes in such a way that the selected path is followed at the desired velocity, and with acceptable accuracy.

The driver methodology has postulated human operator models constructed within the framework of the successive organization of perception theory [10]; the driver models contain aspects of compensatory, pursuit and precognitive elements. These act in series or in parallel (as in a dual control mode). The particular active elements utilized depend on how efficiently the driver uses perceptual information for the specific task at hand.

The essential feature of this approach suitable for the mariner/vessel closed loop system concept is that each of the above elements be replaced by mathematical surrogates which quantitatively describe their interactions. Thus, mathematical models are required which mimic specific functions of the mariner. These functions can be generally categorized into an estimation function, a decision function and a command/control function [11]. In general, manual control theory is replete with examples of previous modeling efforts attempting to mimic these functions. As would be expected, the simplest and most thoroughly studied function of the human is the control function. Specifically, previous research has focused on the closed-loop compensatory control subsystem for regulation tasks.

The most difficult function of the mariner to model is the estimation function since this relies on learned response (behavior) patterns. Driver modeling is similar in nature because in general, there is sufficient roadway preview, contrast and texture in the surrounding environment to permit perception of the roadway and the vehicle output motions as independent entities. As such, a skilled driver can take advantage of this preview to structure a control mechanism. This preview aspect permits the driver to anticipate the desired path. The analogy to a mariner model is clear; the difficulty is involved in postulating mathmatical models that are used to quantify these effects.

In terms of path following control function, driver models assume that the human's behavioral components are intrinsically simple allowing for a direct observation of, for example, required path curvature. In addition, the driver is allowed perception of path and heading errors and the commanded heading rate due to path curvature and car speed [12]. This characteristic is directly transferable to the mariner's perception of the required radius of curvature to negotiate a turn. The required rudder command is thus considered a preplanned open-loop control strategy. The mariner's estimation and decision functions are designed to acquire and process the necessary information for just such a strategy.

Experiments have been performed utilizing man-in-the-loop simulation in order to: (1) validate the driver model, and (2) identify the model parameters. Typically, this validation is performed in a stochastic sense, i.e. the mean and variance are matched to model predictions (also mean and variance). Inter-subject variability is incorporated in these models by allowing sufficient random components. These components are averaged out during overall model validation experiments.

Various scene parameters have been used in validation; i.e. road curvature, wind disturbance and visibility conditions [13]. Reduced visibility conditions have the greatest impact on system performance and direct analogies can be drawn to mariner performance. The most important factors from the driver's point-of-view are geometric properties of size, shape, texture, and photometric properties such as illuminance, reflectance and color. Atmospheric attenuation and scattering (which act to reduce contrast and desaturate colors) decrease distances over which an observation is made. The driver's (mariner's) perceptual processes--modeled by the estimation function in the PON--must extract usable information from the scene. Under adverse visibility conditions, atmospheric and/or lighting properties restrict the road visibility due to contrast reduction and this restricted "preview" has been shown to affect driver steering performance. Effects under nighttime conditions are more complicated. Illumination can be extremely non-uniform. Scattering and backscatter provide a complex distribution of luminance in the visual scene. These effects, along with glare sources, cause the contrast to rapidly attenuate with increased range.

Visual perception models have been developed for drivers which involve steering to an aim point down the road [14]. This is directly analogous to the decision logic for the mariner to obtain the desired control. The dynamics of this simple model have been validated with man-in-the-loop simulations. It was found that the look ahead or preview time constant was dependent upon vehicle

speed and tended to decrease for restricted views. Generally speaking, preview times were found to be on the order of the vehicle time constant in the basic mode of response.

This operator characteristic is incorporated directly in the decision logic of the mariner. Here, preview times are nominally on the order of 60-120 seconds, representing approximately the time constants of the vessel. Decreased visibility, increased stress or workload levels would tend to reduce this parameter. Basically, the operator's anxiety level directly impacts on this parameter value. As this parameter decreases, more oscillatory control behavior is observed in the models. Specific experiments will be structured to identify this important decision parameter and functionally relate it to night/day, visibility, glare, fog, and workload. The decision model attempts to mimic changes in mariner behavior as a consequence of the visual scene. Decreased preview time reduces the system bandwidth which results in increased heading rate deviations.

Other previous mariner research was performed at Delft University, The Netherlands [6]. This research focused on modeling the helmsman in a pursuit tracking task. The desired heading command consisted of a series of steps of randomly distributed amplitudes and durations. The basic conclusions validated by rather simple experiments can be characterized as follows: (a) the helmsman's rudder commands consist of discrete steps, and (b) a change of heading consists of four phases. During the first phase the helmsman generates an output in order to start the ship rotating, then during the second phase, the rudder is kept amidships. During the third phase, the helmsman stops the rotating motion of the ship when the desired heading is achieved with only a small rate of turn (the desired state), and the fourth phase begins a period of zero rudder angle. If the rate of turn is not small enough, there will be an overshoot. To achieve the desired state the cycle is repeated starting with the first phase

again. To construct a suitable model, the "internal model" concept was used. (The internal model concept was perhaps most fully developed at SCI (Vt.) by several years of human operator modeling technology summarized in man-machine systems review [15]. Specific tracking tasks were analyzed by constrasting assumed variations in the the operator's internal model relative to actual system variables. It was shown that closed-loop system performance degraded as the internal model became more simplistic; i.e. when the human observed or "thought" what was happening deviated from the true situation).

The internal model presupposes an approximate model of vessel dynamics obtained by the mariner by a learned response. When the actual ship dynamics differ from the helmsman internal model, after sometime, he will detect a difference between predicted and actual ship state, and come to a new decision as to what control strategy to effect. In this way, the discrete character of the helmsman output may be explained, (One interesting conclusion of the validation experiments was the fact that for very large ships, the subjects could hardly recognize whether the ship was directionally stable or unstable, i.e. their internal model was not complex enough).

In this research the concept of estimator, decision maker and commander was also utilized. Mathematical equations were derived to properly characterize the switching logic appropriate to the four phases observed in the experimental data. One parameter corresponding to the "preview" time constant, for example, was identified as 100 sec [16]. This corresponds to the time constant in the PON model characterizing the decision threshold for region #1. Substantial effort was expended into simulation studies to obtain parameter values corresponding to the threshold (decision) model.

It must be pointed out that the Delft University experiments attempted to model a rather restrictive control task, i.e. a

helmsman tracking heading commands from a compass with no aids other than rudder and heading indicators. However, the basic approach utilizing present day human operator control technology is similar in spirit to the more complete mariner model developed under the current effort.

APPENDIX F
PROCESS OF NAVIGATION MODEL

F.1 INTRODUCTION

For large vessels maneuvering in and out of harbors, the "mariner" typically consists of a pilot and a helmsman. The pilot issues rudder and heading (or course) commands to the helmsman, based on his intentions and his assessment of the vessel state (position, velocity, heading, heading rate). To estimate vessel state, the pilot processes information he receives from his observation of buoys, radar, instruments, and surrounding terrain. He also utilizes previously learned information about the harbor situation and his estimates of such environmental disturbances as wind and current. It is this overall process, from information input to vessel control output, which is addressed by the process of navigation model.

In this context, the process of navigation includes the receipt of information from all significant sources, the processing of this information by the mariner, the evaluation of the processed information with respect to mariner intentions, and the resulting vessel control. The process is not strictly deterministic, due to random and other unknown errors (perceptual errors, instrument errors, etc.) and disturbances (wind gusts, currents, etc.).

The purpose of the model is to quantify the various relationships and interactions which comprise the process of navigation. With this objective, the model has evolved as follows: A comprehensive data base was collected from expert interviews (Appendix B), literature review, and available experiment results. From this data base evolved

NOTATION AND DEFINITIONS

Vessel States*:

CTD ..... cross track deviation

$\dot{CTD}$ ..... cross track rate

ATP ..... along track position

$\dot{ATP}$ ..... along track rate

H .... heading

$\dot{H}$ .... heading rate

R .... rudder position

Mariner Observation Parameters (true values*):

d_i ...... distance to buoy i

α_{ij} ..... angle between buoys i and j

ψ_i ...... angle off the bow of buoy i

$\dot{\psi}_i$ ...... rate of change of ψ_i

θ .... orientation of desired track

β_i ...... angle between buoy i, the mariner and the desired track ($\psi_i + H - \theta$)

d_{ij} ..... difference in distances to buoys i and j ($d_i - d_j$)

$\alpha_{ijk\ell}$ ... difference in the angles between buoys i and j, and buoys k and ℓ ($\alpha_{ij} - \alpha_{k\ell}$)

β_{ij} ..... sum of angles relative to track of buoys i and j ($\beta_i + \beta_j$)

h .... compass reading

v .... speed log

r .... rudder indicator

Decision/Control Variables:

H_d ...... desired heading** (similar notation for heading rate)

H_e ...... heading error

H_I ...... desired track intercept angle

R_d ...... rudder command

---

*True values, as distinguished from observed values. Observed values, or estimates, are denoted with a "hat", such as $\hat{h}$ for observed compass reading.

**"Heading," or orientation, not direction of travel.

qualitative descriptions of the elements of the navigation process, as exemplified in Appendix C where aid utilization is described for several situations. From these qualitative descriptions, quantitative relationships were formulated for the various facets of the navigation process, drawing where possible from previous modeling work (particularly for steering control actions). Finally, these quantitative relationships were integrated into a coherent structure, which also provides for convenient user interface.

The overall structure of the resulting model is shown in Figure F.1. As shown, the structure identifies the two human elements (pilot, helmsman), the vessel and propulsion characteristics, the harbor geometry and environment, the on-board instruments, the aids to navigation, and various error sources. The following two sections present the technical details of the models used in this study to represent (1) pilot and helmsman, and (2) the other elements contained in the Process of Navigation.

F.2 MODEL DETAILS - PILOT AND HELMSMAN

For steering the vessel, a relationship exists between the pilot and helmsman where the pilot gives instructions to the helmsman in two forms--rudder commands and heading* commands. For these two situations, the pilot acts in either of two roles--as a "controller" or as a "monitor." When he is giving direct rudder commands, he is in an active controller mode. He is then modeled by three sequential but interrelated functions (indicated in Figure F.1):

---

*Heading commands refer to the vessel heading (in particular, compass reading), not the actual vessel direction of travel. The direction of travel may differ from the heading due to the effects of current, wind and sideslip. These effects, in conjunction with the desired direction of travel, are taken into consideration by the pilot in determining the desired heading.

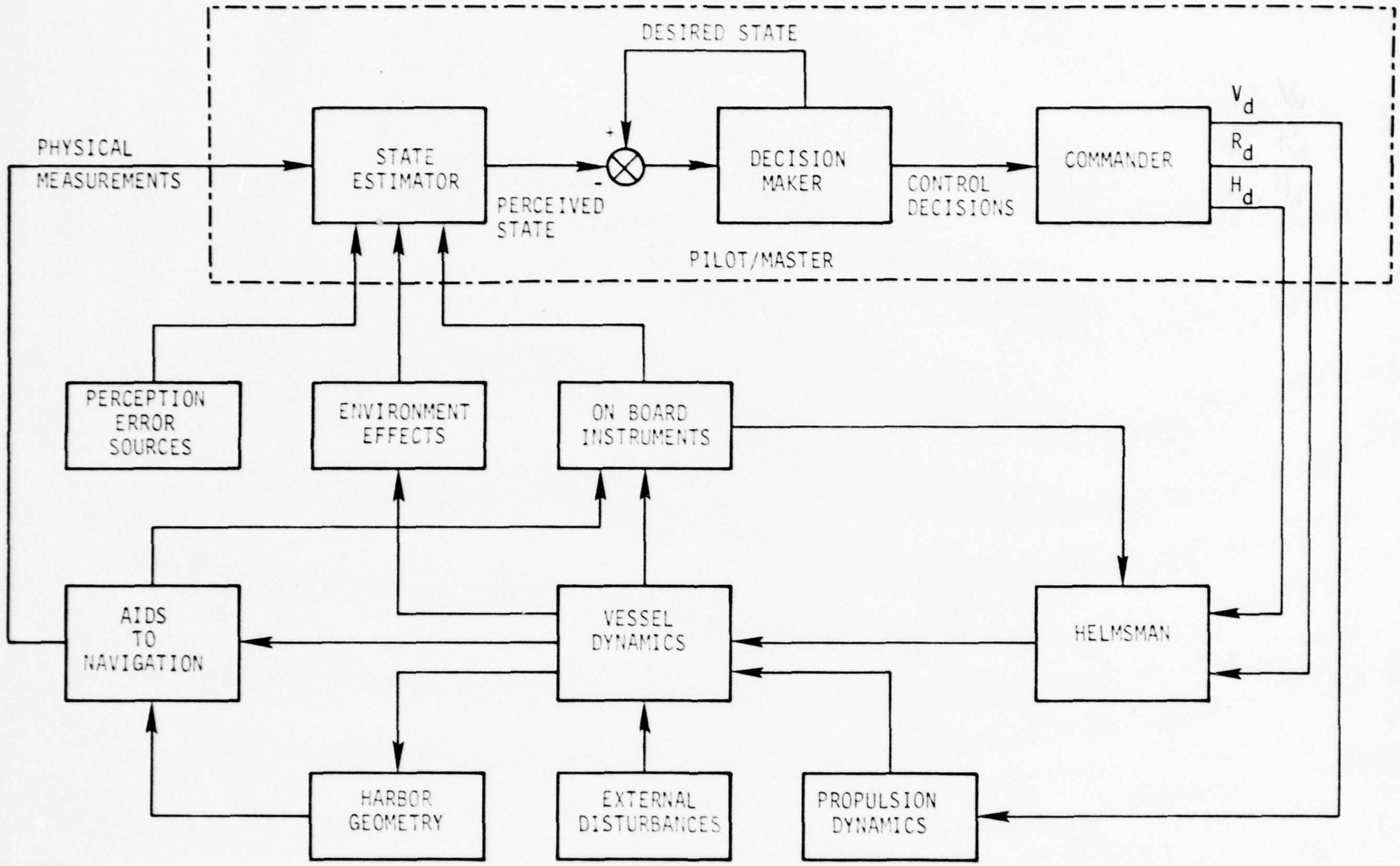


Figure F.1 Process of Navigation Model

(1) Estimator - determine the state of the vessel with with respect to the desired course and other decision variables.

(2) Decision Maker - determine what action, if any, must be made to correct the vessel situation or to make a regular change in heading. These decisions are often referred to as "guidance."

(3) Commander - command the desired heading or rudder settings to the helmsman which will provide the required vessel action.

The pilot's active mode is further broken into what are referred to as (1) tactical and (2) strategic situations. Tactical situations include:

(1) passing or overtaking another vessel

(2) avoiding imminent grounding.

Tactical situations have the higher priority, as far as pilot action is concerned. However, they are not as dependent on the aid configuration as are the strategic tasks. Thus, the tactical situations were not studied in Phase I, but provisions for them are included in the pilot model. Strategic situations include:

(1) Making a course change (as around a bend)

(2) Returning to track*

(3) Entering a channel

* Returning to track has both tactical and strategic properties; for the Phase I model, return-to-track is treated as a high-priority control strategy, super-imposed on the course change and channel entrance strategies. In this way, track keeping will be maintained during course change and channel entrance.

These strategic situations are encompassed in the Phase I pilot model.

When the pilot determines that it is appropriate to do so, he gives the helmsman a desired heading to steer and reverts to a passive monitor mode. In the monitor mode, the pilot's attention level goes down, and he only resumes the active controller mode again, when (1) a change in heading is desired or (2) the pilot detects a potential deviation from the desired track beyond a pre-set threshold.

When the pilot is in the active role, the helmsman does only what he is told by the pilot. The helmsman can then be represented as (1) a small time delay (the time between when he is given a rudder command and when he makes the rudder deflection), and (2) an error source (representing the inaccuracy in his following the commands.) When the pilot is in a passive role and has given the helmsman a heading command, the helmsman proceeds to steer to hold that heading. He then must (1) judge the error in the vessel heading and heading rate, (2) decide if a compensating change in rudder setting is required, and (3) input this rudder change directly through the helm. This is referred to as a compensatory tracking task in the man-machine modeling literature. It can be seen that in this role, the helmsman has the same three sequential functions as does the pilot in the active mode. These functions are now discussed.

F.2.1 Pilot

As just explained, the pilot is represented as a sequence of three functions - State Estimator, Decision Maker, and

Commander. Each of these functions can be described as a group of inputs, a group of outputs, and a series of functional steps which produce the desired outputs from the given inputs. These functional steps are further characterized by a series of equations, numerical tables, and logical decisions. Thus, the physical perception, deductive reasoning, and trained oral response of the pilot is represented by a general mathematical model. This mathematical model is, in turn, converted into a digital computer subroutine which is part of the Process of Navigation computer simulation.

F.2.1.1 State Estimator Description

F.2.1.1.1 Overview

This section describes in detail the "State Estimator" portion of the pilot model. It is known that several additional estimator functions beyond those currently implemented (such as processing of radar and radio aid information) may be required for the Phase II model. It is also expected that some of the logic or techniques utilized will have to be revised pursuant to thorough examination of model performance, in conjunction with the results of Phase II validation activities. The description presented in this section will focus on the State Estimator as currently implemented. The additional Phase II modeling and validation efforts are discussed in Section 3.6 of the main body of this report.

The purpose of the State Estimator is to quantify the pilot's role of identifying, in real time, the status of the vessel. The pilot accomplishes this task by perceiving the

visual aids and vessel displays, and correlating these perceptions with vessel status by using previously learned relationships between perceptions and status and also by performing various mental computations in order to "mathematically" deduce vessel status. The estimator model attempts to duplicate the input-to-output characteristics of the pilot's estimation process to the fidelity necessary to accomplish the objectives of this effort.

Within each simulation time increment, the State Estimator supplies to the subsequent pilot submodels estimates of one or more of the following pertinent vessel "states":

(1) Cross Track Deviation (CTD)

(2) Cross Track Deviation Rate ($\dot{CTD}$)

(3) Along Track Position (ATP)

(4) Along Track Position Rate ($\dot{ATP}$)

(5) Heading (H)

(6) Heading Rate ($\dot{H}$)

(7) Rudder Position (R)

The State Estimator does not identify which states are important, nor does it identify suitable pilot control action; these functions are relegated to the "Decision Maker" and "Commander" submodels, respectively.

The process by which the State Estimator obtains estimates of the previously listed vessel states consists of five basic steps:

(1) Identification of information available.

(2) Estimation of the anticipated errors associated with the available information and designation of the information to be utilized.

(3) Determination of weighting factors (to be applied when redundant information is usable).

(4) Generation of the actual measurements (observations).

(5) Combining of measurements to form final state estimates.

These basic state estimator functions are described in the following subsections. An overview flow chart of the State Estimator is presented in Figure F.2.

F.2.1.1.2 Identification of available information

The state estimator is currently designed to utilize visual information from buoys, USCG ranges and selected vessel displays (compass, rudder indicator, speed log). The state estimator logic also presumes that the pilot is aware of the orientation of the desired track (the track heading).

Vessel displays are always considered "available"; although the capability to assess the impact of display malfunctions exists, this is not considered of first order study interest. At present, the constraints on buoy/range availability are as follows:

(1) They must be within the prescribed visibility limits (a simulation input)*;

(2) They must not be behind the vessel, and

(3) For "nighttime" simulations, they must be lighted.

Buoys (and ranges) provide distance information, angles between buoys, angles off the bow, and angle rates. For the purposes of this appendix, the terminology used to describe the available information is as follows:

d_i = distance to buoy i

*At the present time, only discrete detection/availability thresholds are modeled. Of foremost importance is buoy visibility. Based on the sensitivity studies conducted, visibility was shown to be an important model input. Hence, further effort will be devoted to establishing more realistic availability criteria.

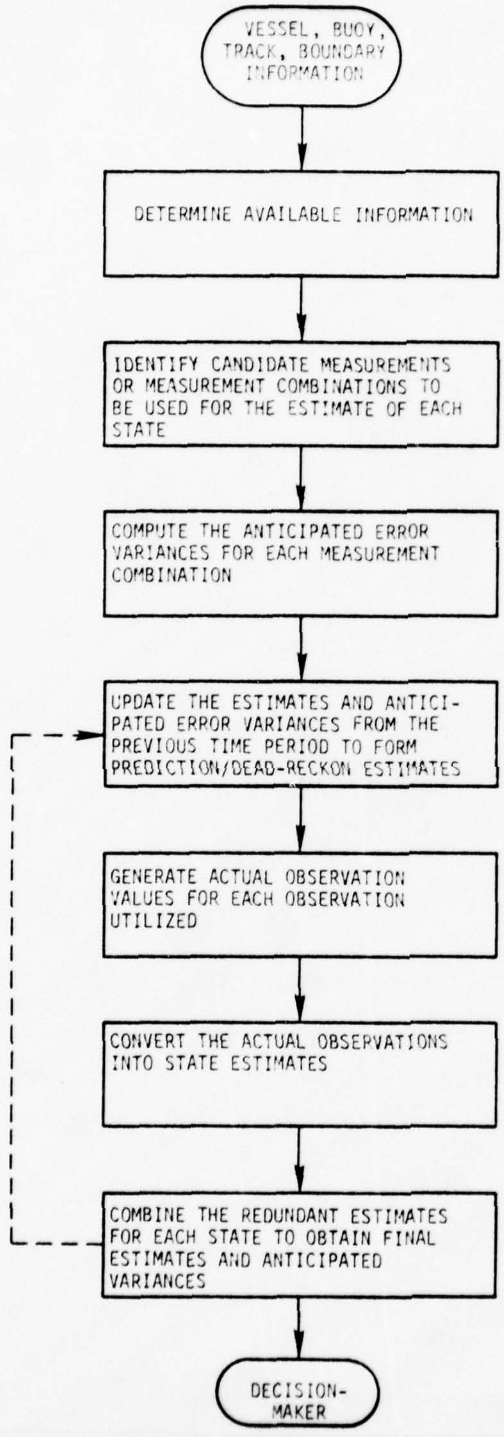


Figure F.2 Pilot State Estimator Model Overview

α_{ij} = angle between buoys i and j (subtended at the mariner)

ψ_i = angle between buoy i, the mariner and the bow of the vessel

$\dot{\psi}_i$ = rate of change of ψ_i

H = vessel heading

V = vessel speed

R = rudder position

θ = orientation of the desired track

To estimate cross-track deviation and along-track position, the available information is used to construct "lines of position" and their intersections. This is a computational convenience (i.e. a functional aspect of the model), and it is not necessarily presumed that the mariner is cognizant of specific lines of position. The distance to a buoy (d_i) and the angle between buoys (α_{ij}) each produce lines of position. Utilizing a standard orthogonal (X-Y) coordinate system, where (X_v,Y_v) is the vessel position (or locus of positions) and (X_i,Y_i) are the known buoy locations, the lines of positions can be given as shown below:

Type of Observation ("Direct")	Definition	Line of Position (Locus of X_v,Y_v Values)
d_i	Distance to buoy i	$d_i = \sqrt{(X_v-X_i)^2 + (Y_v - Y_i)^2}$
α_{ij}	Angle between buoys i and j	$\cos \alpha_{ij} = \dfrac{D_i^2 + D_j^2 - D_{ij}^2}{2D_iD_j}$ where $D_i^2 = (X_v-X_i)^2 + (Y_v-Y_i)^2$; $D_j^2 = (X_v-X_j)^2 + (Y_v-Y_j)^2$; $D_{ij}^2 = (X_i-X_j)^2 + (Y_i-Y_j)^2$

The reader will note that the above equations have not been solved for Y_v as a function of X_v in the usual manner. Some of these expressions are very complex, so computation techniques were developed which did not require solving the equations. This also permits the expressions to be presented in the simplest, most intuitively informative manner.

The two line of position (LOP) equations given above are based on "direct" observations. Much additional information is obtainable from buoys and known to be utilized by the mariner. As a result, four other LOP's were identified and incorporated into the State Estimator logic. These are given below:

Type of Observation ("Indirect")	Definition	Line of Position (Locus of X_v, Y_v Values)
β_i	Angle between buoy i, the mariner and the desired track. ($\beta_i = \psi_i + H - \theta$)	$Y_v = \frac{(X_v - X_i)}{\tan(\beta+\theta)} + Y_i$
d_{ij}	Difference between the distances from the vessel to buoy i vs. buoy j.	$d_{ij} = d_i - d_j$ *
$\alpha_{ijk\ell}$	Difference between the angle between buoys i and j, and the angle between buoys k and ℓ.	$\alpha_{ijk\ell} = \alpha_{ij} - \alpha_{k\ell}$ *
β_{ij}	Sum of the angles of buoy i relative to the track and buoy j relative to the track (a sum of zero indicates equality, since angles to the left of track are negative)	$\beta_{ij} = \beta_i + \beta_j$ *

*Specific equations can be obtained from the preceding equations, if desired.

The information available from buoys (other than the angle and distance difference data) is depicted in Figure F.3. The specific manner in which this information is used is a function of the particular state being estimated. This is discussed in the next subsection.

F.2.1.1.3 Error models and identification of information utilized

For each state, special logic has been designed which processes the available information in order to identify that which is utilized. This logic varies from very simple to somewhat complex, basically as a function of the type and amount of information which might be used.

In general, the "final" estimate of each state is based upon a weighted average of three components: a primary, a secondary and a prediction (or dead-reckon) estimate. The "weights" applied to each information source are a function of the anticipated errors of each component (anticipated error variances). The specific manner in which the weights are selected is discussed in the next subsection. The purpose of this subsection is to describe how the anticipated error variances are determined and, in turn, how the information to be utilized for each state is selected.

Prior to discussing the above procedure as it relates to each state, it is appropriate to discuss the error models and error modeling techniques utilized.

Error Modeling

In most instances, a mariner has multiple or redundant information by which state estimates can be obtained. He makes a decision, consciously or otherwise, as to which information to use and how much to rely on one information source as compared to another.

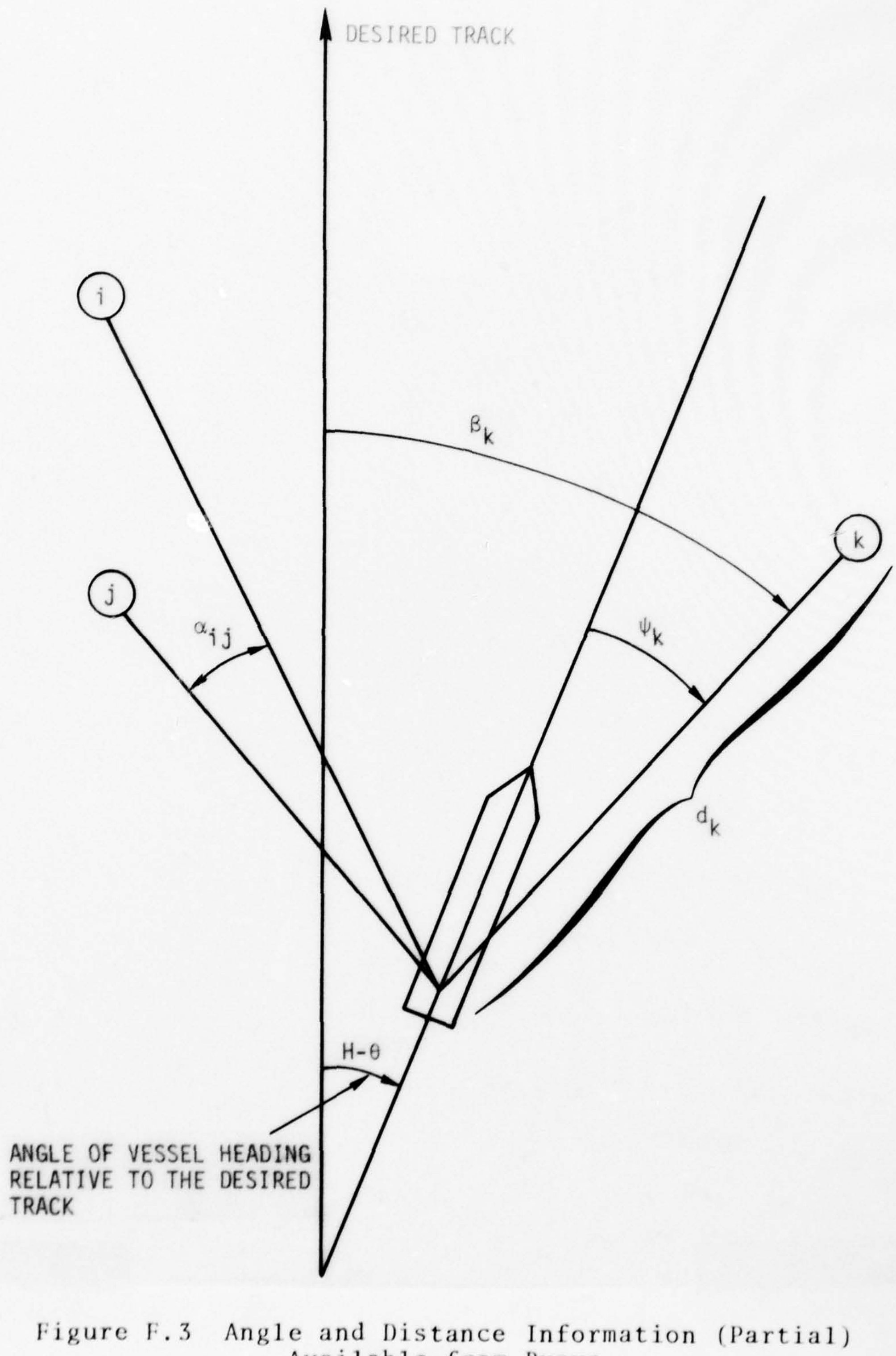


Figure F.3 Angle and Distance Information (Partial) Available from Buoys

The mechanism used in the model to determine which information is used is based upon conventional statistical estimation techniques, as described below.

In loose terms, multiple or redundant state estimates (dead-reckoning primary, secondary) are weighted according to the model's representation of the pilot's confidence in each. This confidence is a function of how well the pilot feels he can measure (perceive) various information types (distances, angles, etc.), and his understanding of the impact of estimation errors in the particular situation geometry. Thus, the selection of information to utilize and their associated weights is based upon the pilot's "anticipated" error variances. The model accepts two totally separate sets of error variances; "anticipated" error variances (which form the basis for the weighting), and "actual" error variances (which are used by the simulation logic to generate actual observation errors). While the model is currently being executed utilizing equal values for anticipated and actual error variances (implying that the pilot has a correct understanding of his perception ability), the capability exists to alter these values as a part of model tuning or calibration, in the event that data is obtained indicating that anticipated and actual errors are not equal.

In addition to the use of both anticipated and actual error variance data, another key element of the error modeling is the partitioning of the errors into random and bias terms. Specifically, all errors have the following components:

(1) a bias; randomly selected at the beginning of each transit,

(2) a "common" error; randomly selected for each time period, and,

(3) a random error.

The subdivision of errors into random and bias components is a standard simulation technique used to account for the fact that human operator errors, as well as many instrument errors, contain a significant bias term, often of greater magnitude than their random error. In the current simulation, an additional error component has been added, referred to as a "common" error. This common error functions as a bias applied to all observations of the same type made at the same time. This provides for a statistical mechanism by which to account for the fact that the comparison of equal distances or equal angles can be very accurately performed. For example, the difference between two distances can be more accurately estimated (perceived) than either of the distances themselves. In the current implementation of the model, this is accounted for by the fact that the common error (as well as the bias) cancels out. Total error variance is thereby reduced.

For clarity of terminology, the following notation is used:

b_d bias error term for distance observations

c_d common error term for distance observations

e_d random error term for distance observations

Similar notation is used for the other observation types (α, h, etc.)

Anticipated error variances (as well as actual variances) are input to the model for each type of observation that the mariner may be able to make. These include the following:

h: compass reading

v: vessel log

r: rudder indicator

d_i: distance to a buoy

α_{ij}: angle between buoys

ψ_i: angle off the bow

$\dot{\psi}_i$: angle rate, relative to a buoy

The error models used for each type of direct observation can be generically categorized in one of two basic types. An example of the first type is compass heading estimate given by $\hat{h} = h + b_h + e_h$ where h is the true heading, b_h and e_h represent sample functions generated from a zero-mean Gaussian random process* with fixed (input) variance. For one particular execution of a Monte Carlo run, the b_h is selected from this random process and remains a constant (bias). For each integration step, e_h is a sample function, also generated from a zero mean process. This type of observation is modeled by additive noise terms which are not functions of the actual or true compass reading. A second type of error model is utilized for distance and angle measurements. For example, the estimate off the bow is given by $\hat{\psi} = \psi(1 + b_\psi + c_\psi + e_\psi)$ where ψ is the true angle (uncorrupted) with random variables represented by b_ψ, c_ψ, e_ψ. The uncertainty in the measurement is proportional to the true value, indicative of measurement uncertainty increasing as the true angle increases. All of the observations fall into one of these two categories.

From the error models associated with the direct observations, error models can be constructed associated with the "indirect" observations. This was done for each of the indirect observations associated with the lines of position previously described (i.e., β_i, d_{ij}, β_{ij}, and $\alpha_{ijk\ell}$).

---

*Within Phase I, all estimation errors were assumed to be Gaussian. This assumption was considered appropriate for the Phase I effort, but will be re-evaluated in Phase II. For the most part, all data obtained in Phase II which permits quantification of the error magnitudes will also permit an analysis of distribution forms. Such analyses will be accomplished and the distributions utilized in the model will be altered as needed.

All of the observation types, their error models, and the resulting anticipated error variances are given in Table F.1.

The anticipated error variance equations are derived from standard statistical theorems. For example, where

$$\hat{h} = h + b_h + e_h$$

and b_h and e_h are independent, then the variances of the error $(h-\hat{h})$ is simply the sum of the component error variances;

$$\sigma_h = \sigma^2_{b_h} + \sigma^2_{e_h}$$

For those observation types which are based upon sums or differences of direct observations, the anticipated error equations suitably take into account the non-independent terms (common and bias components). For example, consider distance difference observations, d_{ij}:

$$\hat{d}_{ij} = \hat{d}_i - \hat{d}_j$$

Using the expressions for $\hat{d}_i$ and $\hat{d}_j$, the above may be written as:

$$\hat{d}_{ij} = d_i(1 + b_d + c_d + e_{d_i}) - d_j(1 + b_d + c_d + e_{d_j})$$

Note that the random errors (e_d's) are subscripted to reflect the respective buoys. The common and bias errors are not subscripted because they are to be randomly selected independent of the buoys. The above expression may now be written as follows:

$$\hat{d}_{ij} = d_i - d_j + (d_i - d_j)(b_d + c_d) + d_i e_{d_i} + d_j e_{d_j}$$

Table F.1

Error Models and Variance Equations

OBSERVATION TYPE	OBSERVATION ERROR MODEL	ERROR VARIANCE
$\hat{h}$	$\hat{h} = H + b_h + e_h$	$\sigma^2_{\hat{h}} = \sigma^2_{b_h} + \sigma^2_{e_h}$
$\hat{v}$	$\hat{v} = V + e_v$	$\sigma^2_{\hat{v}} = \sigma^2_{e_v}$
$\hat{r}$	$\hat{r} = R + b_r + e_r$	$\sigma^2_{\hat{r}} = \sigma^2_{b_r} + \sigma^2_{e_r}$
$\hat{d}_i$	$\hat{d}_i = d_i(1 + b_d + c_d + e_d)$	$\sigma^2_{\hat{d}_i} = d_i^2(\sigma^2_{b_d} + \sigma^2_{c_d} + \sigma^2_{e_d})$
$\hat{\psi}_i$	$\hat{\psi}_i = \psi_i(1 + b_\psi + c_\psi + e_\psi)$	$\sigma^2_{\hat{\psi}_i} = \psi_i^2(\sigma^2_{b_\psi} + \sigma^2_{c_\psi} + \sigma^2_{e_\psi})$
$\hat{\alpha}_{ij}$	$\hat{\alpha}_{ij} = \alpha_{ij}(1 + b_\alpha + c_\alpha + e_\alpha)$	$\sigma^2_{\hat{\alpha}_{ij}} = \alpha_{ij}^2(\sigma^2_{b_\alpha} + \sigma^2_{c_\alpha} + \sigma^2_{e_\alpha})$
$\hat{\beta}_i$	$\hat{\beta}_i = \hat{\psi}_i + \hat{h} - \theta$	$\sigma^2_{\hat{\beta}_i} = \sigma^2_{\hat{\psi}_i} + \sigma^2_{\hat{h}}$
$\hat{d}_{ij}$	$\hat{d}_{ij} = \hat{d}_i - \hat{d}_j$	$\sigma^2_{\hat{d}_{ij}} = (d_i - d_j)^2(\sigma^2_{b_d} + \sigma^2_{c_d}) + (d_i^2 + d_j^2)\sigma^2_{e_d}$
$\hat{\alpha}_{ijk\ell}$	$\hat{\alpha}_{ijk\ell} = \hat{\alpha}_{ij} - \hat{\alpha}_{k\ell}$	$\sigma^2_{\hat{\alpha}_{ijk\ell}} = (\alpha_{ij} - \alpha_{k\ell})^2(\sigma^2_{b_\alpha} + \sigma^2_{c_\alpha})$ $+ (\alpha_{ij}^2 + \alpha_{k\ell}^2)\ \sigma^2_{e_\alpha}$
$\hat{\beta}_{ij}$	$\hat{\beta}_{ij} = \hat{\beta}_i + \hat{\beta}_j$	$\sigma^2_{\hat{\beta}_{ij}} = (\psi_i + \psi_j)^2(\sigma^2_{b_\psi} + \sigma^2_{c_\psi}) + (\psi_i^2 + \psi_j^2)\sigma^2_{e_\psi}$ $+ 4\sigma^2_{\hat{h}}$
$\hat{\dot{\psi}}_i$	$\hat{\dot{\psi}}_i = \dot{H} + \left(1 + \frac{2\|\psi\|}{\pi} + \frac{\|\dot{H}\|}{.00349}\right)$	$\sigma^2_{\hat{\dot{\psi}}} = (\sigma^2_{b_{\dot{\psi}}} + \sigma^2_{c_{\dot{\psi}}} + \sigma^2_{e_{\dot{\psi}}})\left[1 + \frac{2\|\psi\|}{\pi} + \frac{\|\dot{H}\|}{.00349}\right]^2$

Since e_{d_i}, e_{d_j}, b_d and c_d are independent, and d_i and d_j are constants (at a given time point), the variance of $\hat{d}_{ij}$ is given by:

$$\sigma^2_{\hat{d}_{ij}} = (d_i - d_j)^2(\sigma^2_{b_d} + \sigma^2_{c_d}) + (d_i^2 + d_j^2)\sigma^2_{e_d}$$

It is appropriate to note that the bias and common terms cancel, to the extent that d_i and d_j are equal. They do not cancel when individual distance measurements ($\hat{d}_i$) are made and used. Further, the relationship between $\sigma^2_{b_d}$ and the sum of $\sigma^2_{c_d}$ and $\sigma^2_{e_d}$ reflects the amount of an individual distance observation that is a bias as compared to a time varying random noise.

Table F.2 presents the anticipated (and actual) observation error variances as used in the current version of the model. For the most part, the specific error values were selected based upon past SCI (Vt) experience, not all of which pertains to a marine environment. Some amount of "tuning" of these values was done in order to obtain better agreement with the initial CAORF data that was obtained. Generally, the error values were increased from what prior experience would indicate. Also, further adjustments were made, regarding the division between bias, common and random errors, so that the model would utilize buoy configurations in the general manner indicated by the interview results. Adjustments in the relative magnitude of the error variances and re-apportionment of the error components is a standard mechanism by which to cause the model to utilize the proper buoy information and to switch from one primary observation source to another at the proper times. The extent to which the current model has been calibrated in this manner is only preliminary.

The following points summarize the implications of Table F.2 and the discussion of the above paragraph:

(1) Distance observations are within 25% of the true value 80% of the time.

(2) Angle-between-buoy estimates are within 35% of the true value 50% of the time.

(3) Angle-off-the-bow estimates are 25% worse (in total standard deviation) than angles between buoys.

Table F.2

Preliminary Anticipated and Actual Error Values[1]

OBSERVATION	σ_b	σ_c	σ_e	σ_{TOTAL}
$\hat{h}$	0.006	0.	0.006	0.009
$\hat{v}$	0.	0.	2.000	2.000
$\hat{r}$	0.[2]	0.[2]	0.[2]	0.[2]
$\hat{d}_i$	0.138	0.126	0.056	0.195
$\hat{\psi}_i$	0.288	0.288	0.504	0.648
$\hat{\alpha}_i$	0.231	0.231	0.403	0.519
$\hat{\dot{\psi}}$	0.	0.	0.001	0.001

[1]Units are radians for $\hat{h}$, $\hat{r}$ and kts for $\hat{v}$. The remainder are non-dimensional.

[2]Rudder position data is not used by current version of the pilot. For this reason, no effort was made to identify errors.

The magnitudes of those errors modeled as absolutes are self-explanatory. As mentioned, the partitioning of the errors among the error components was based primarily on functional requirements; additional justification is not available.

The following paragraphs present the specific logic used to identify the information utilized for each state and the manner in which the primary, secondary and prediction/dead reckoning anticipated variances are computed. These discussions will be presented in the order thay they are actually computed, since the estimates for some of the states are used in the estimation of others.

Heading Rate

The State Estimator currently assumes that heading rate information is obtained primarily from observations of the rate of change of angles off the bow ($\dot{\psi}$ observations). The estimation error model for observations of $\dot{\psi}$ prescribes that the estimation errors are smallest when the buoys are finest off the bow. As a result, the buoys selected for heading rate estimation are those whose 'ψ' values are smallest (in terms of absolute value). In the current model, USCG ranges are modeled in a similar manner as buoys, i.e. a range is essentially a set of two buoys. The buoy selection logic permits no more than one of the range lights to be used for heading rate estimation.

It is appropriate to mention that in virtually all buoy configurations that are expected to be evaluated, there will typically be two buoys which are reasonably directly in front of the vessel. Thus, the vessel forward motion will have no noticeable effect on the $\dot{\psi}$ observation. As a result, for simplicity, the assumption was made that the heading rate ($\dot{H}$) is approximately equal to the buoy angular rate of change ($\dot{\psi}$).

The heading rate estimates are also "smoothed" with a predictor/dead reckon estimate. The dead-reckon estimate is made by merely assuming that the heading rate will be a constant from one time period to the next. This is a necessary assumption since no "acceleration" information is modeled. A more accurate prediction of heading rate, based, for example, on rudder position, was not considered warranted or realistic. Thus, the dead reckon estimate for heading rate for time 't' is given by

$$\dot{H}_{DR,t} = \hat{\dot{H}}_{FINAL,t-1}$$

where $\hat{\dot{H}}_{FINAL,t-1}$ is the final estimate of the previous time increment.

The variance of the dead-reckon estimate is:

$$\sigma^2_{\dot{H}_{DR,t}} = \sigma^2_{\dot{H}_{FINAL,t-1}} + \Delta t^2 \, \sigma^2_n$$

where

$\sigma^2_{\dot{H}_{FINAL,t}}$	is the variance of the final estimate of the previous time period (how this is computed is described in the next subsection)
Δt	is the simulation time increment
σ^2_n	is a "process noise" term indicating uncertainty in how much the heading rate may change in a given time period.

As will be described later, the variance of the dead-reckon estimate, in conjunction with the variances of the primary and secondary estimates ($\hat{\dot{\psi}}$ values), is used to establish the weighting factors by which the final weighted average is obtained.

The specific value of the process noise term was based upon an analysis of actual fluctuation in the heading rate, based on preliminary model executions. In relative terms, the process noise term is large, and almost no dead-reckoning of heading rate is performed. To do so induces a lag in the estimate which degrades pilot performance more than the nominal noise in the observations.

Heading:

Heading estimates within the model are obtained from a primary estimate (compass) and a prediction/dead-reckon estimate. The prediction estimate for time period Δt is obtained as follows

$$H_{DR,t} = \hat{H}_{final,t-1} + \Delta t\ \hat{\dot{H}}_{final,t-1}$$

where

$\hat{H}_{final,t-1}$ is the previous final heading estimate

$\hat{\dot{H}}_{final,t-1}$ is the previous final heading rate estimate

Δt is the simulation time increment

The variance of the dead-reckon estimate is given by

$$\sigma^2_{H_{DR,t}} = \sigma^2_{H_{final,t-1}} + \Delta t^2\ \hat{\dot{H}}_{final,t-1}$$

The variance of the primary/compass observation can be taken directly from Table F.2.

Cross Track Rate/Along Track Rate

In the initial formulation of the model, cross-track rate and along-track rate were to be estimated via fitting a straight line through the previous (5 to 10) cross track/along track position estimates. The line was to be fitted via least squares, except that rather than minimizing the sums of squares of the deviations about the line (as is usual) the sums of squares were scaled by their respective anticipated variances. In this manner, the line would tend to be closer to the position estimates which had smaller variances, and would tend to ignore position fixes with larger uncertainty.

This methodology induced considerable lag in the position rate estimates. By reducing the number of points to which the line was fit (from 10 to 5), the lag was reduced, but the final rate estimates had too high of a variance to be usable. The preliminary conclusion drawn from this result was that, except in calm/no current situations, when very little rudder is used, the pilot cannot easily estimate position rates by comparing past positions. Ultimately, the line-fitting technique was bypassed. Since it is still a part of model, and may well be used in selected situations, the pertinent equations are presented in Table F.3.

In lieu of estimating cross track rate and along track rate via referencing past positions, an alternative was adopted which essentially implies that the pilot makes an approximate estimate of these states based on his knowledge of his heading, the track heading, the current and his speed. The equations for these estimations are as follows:

$$\hat{C\dot{T}D} = \hat{V}_c \sin(\hat{H}_c - \theta) + \hat{V} \sin(\hat{H} - 30\ \hat{\dot{H}} - \theta)$$

$$\hat{\dot{A}TP} = \hat{V}_c \cos(\hat{H}_c - \theta) + \hat{V} \cos(\hat{H} - 30\ \hat{\dot{H}} - \theta)$$

where

$\hat{V}_c$, $\hat{H}_c$ are the estimated current velocity and heading

θ is the desired track heading

$\hat{H}$, $\hat{\dot{H}}$ are the final vessel heading and heading rate estimates.

The form of the above equations is straightforward. The heading estimate of the vessel is altered (30 $\hat{\dot{H}}$ is subtracted) to account for vessel response delay (i.e. motion of the vessel is more directly correlated with the heading 30 seconds previous, rather than the heading at the time the computation is made). These estimates are not smoothed with secondary or dead-reckoning

Table F.3

Weighted Least Squares Line Fitting Equations

Line Form:	$y = a\ i + b \quad i=1,n$ (no. of time points)
Minimization Objective:	$\sum_{i=1}^{n} \left(\frac{\hat{y}-y_i}{\sigma_i}\right)^2$
Estimate of Slope : (i.e. position rate)	$\hat{a} = \frac{\left(\Sigma \frac{i}{\sigma_i^2}\right)\left(\Sigma \frac{y_i}{\sigma_i^2}\right) - \left(\Sigma \frac{1}{\sigma_i^2}\right)\left(\Sigma \frac{i\ y_i}{\sigma_i^2}\right)}{\left(\Sigma \frac{i}{\sigma_i^2}\right)^2 - \left(\Sigma \frac{1}{\sigma_i^2}\right)\left(\Sigma \frac{i^2}{\sigma_i^2}\right)}$
Position Rate Estimate: (cross track or along track)	$\hat{\dot{CTD}}$ (or $\hat{\dot{ATP}}$) $= \hat{a}/\Delta t$
Anticipated Variance:	$\sigma^2 = \frac{\Sigma \left(\frac{K_2 - K_1 i}{\sigma_i}\right)^2}{\Delta t^2 (K_2^2 - K_1\ K_3)^2}$
where $K_1 = \Sigma \frac{1}{\sigma_i^2}$	
$K_2 = \Sigma \frac{i}{\sigma_i^2}$	
$K_3 = \Sigma \frac{i^2}{\sigma_i^2}$	

estimates. The anticipated variances are obtained by first order linear approximation. This is done by taking the partial derivatives with respect to all of the variables (estimates), and taking the sum of squares of all derivatives multiplied by their respective error standard deviation. The resulting variance of the CTD estimate is given by

$$\sigma^2_{\hat{\dot{CTD}}} = \sigma^2_{\hat{V}_c} \sin(H_c-\theta) + \sigma^2_{H_c} V_c^2 \cos^2(H_c-\theta) + \sigma^2_{\hat{V}} \sin^2(H-30\dot{H}-\theta)$$

$$+ \sigma^2_{\hat{H}} V^2 \cos^2(H-30\dot{H}-\theta) + \sigma^2_{\hat{\dot{H}}} \cos^2(H-30\dot{H}-\theta)30^2V^2$$

A corollary equation was used for along track rate. The anticipated variances in the estimates of current were as follows:

$$\sigma_{V_c} = .25 \text{ (knots)}$$

$$\sigma_{H_c} = 5°$$

Cross Track and Along Track Position Estimation

The State Estimator estimates vessel cross track and along track positions based on the computation of intersections of lines of position (LOP's). This portion of the model is conceptually straight-forward (although algebraically complex). The mariner is presumed to make observations of angles and distances. Within the model, these observations are made, suitably corrupted by observation errors, and are used to define LOPs. The LOP intersections are computed, producing X-Y position estimates. These estimates are then converted into either cross track or along track estimates.

In a typical scenario, the number of potential LOP's is reasonably large. Thus, the number of available pairs of LOP's

is also large. The current version of the model permits the use of only two LOP pairs for cross track and two for along track. There are two separate processing elements which are used to establish which pairs are ultimately used for position estimation. The first processing element has been referred to as the "fast scan" or "culling" logic. This logic encompasses a set of heuristic rules (priority schemes) which are used to identify eight "candidate" LOP pairs for cross-track and eight more for along track. The second processing element selects the "best" two LOP pairs from each set of eight candidate pairs, based on computations of the "anticipated" estimation errors (variances) associated with each pair.

Each of these two processing elements is discussed in the following paragraphs.

"Fast Scan Logic"

The fast scan logic is utilized purely for computational efficiency. Its purpose is merely to constrain the number of LOP pairs for which the variance computations are made.

The only requirement placed upon the fast scan logic to insure its validity is that the LOP pairs identified must include the two "best" pairs (where best is defined by the mariner interviews, and validated by the variance logic). Any additional pairs identified have no impact on the model results; i.e., they are ignored based on the variance computations. Currently, the fast scan logic is used to identify eight candidate pairs. This can be increased or decreased as desired.

The specific fast scan logic (priority scheme) is shown in Tables F.4 and F.5. The logic searches sequentially through the priority scheme, identifying candidate LOP pairs, until eight candidates (for CTD and for ATP) are found.

Table F.4

LOP Pair "Fast Scan" Logic for Cross Track Deviation

PRIORITY	LOP PAIR[1]
1	USCG Range (α_{ij} observation - angle between lights; only if α_{ij} is small[2] and range is "aligned" to track)
2	Equal angles between buoys, pairs, on opposite sides of the channel ($\alpha_{ijk\ell}$ observations). Distances to buoys on left must be nearly equal to those on right. At most, two sets of buoy pairs can be identified.
3	Distance difference to first left and right buoy (d_{ij} observation).
4	Distance difference (d_{ij}) between left and right side buoys <u>other</u> than both nearest buoys (identified and included by Priority 3 logic). Distances must be near equal. Logic does not scan beyond second nearest buoys.
5	Equal angles relative to desired track (β_{ij} observation). Distances to buoys must be near equal.
6	Distance to first left buoy (d_i) and angle between first two left buoys (α_{ij}).
7	Same as Priority 6 for right side buoys.
8	Angles relative to track for first left and right side buoys (two β_i observations).
9	Distance (d_i) and angle relative to track (β_i) from the first left buoy.
10	Same as Priority 9 for right side buoy.

[1] When only one LOP is listed, this is the primary LOP. A second LOP, whose selection is inconsequential (usually a distance or angle off the bow), is used to identify an LOP pair, so that an intersection can be found and a position estimate made.

[2] All criteria for small, large, equality, alignment, etc., are based on simulation inputs, which are changeable. Criteria thus far utilized are preliminary; but model performance does not appear to be sensitive to specific criteria values.

Table F.5

LOP Pair "Fast Scan" Logic for Along Track Position

PRIORITY	LOP PAIR
1	Any angle between buoys (α_{ij}), other than a USCG range, whose value is near zero (reflects taking a "range" off buoys).
2	Angle between next left and right side buoys (α_{ij}) and distance (d_i) to whichever is closer.
3	Angles relative to track (β_i, β_j) for the next left and right side buoys.
4	Distance to next left buoy (d_i) and angle between next two left buoys (α_{ij}).
5	Same as Priority 4 for right side buoys.
6	Distances to next left and right side buoys (d_i,d_j).
7	Distance (d_i) and angle relative to track (β_i) for the next left side buoy.
8	Same as Priority 7 for right side buoy.

"Anticipated Variance" Computations for LOP Pairs

It is fully expected that mariners utilize observations which have proven to be reliable based on their past experience. It is also reasonable to expect that the reliability of observations (lines of positions) can be predicted based upon consideration of the geometries and error statistics. Thus, while the mariner operates based on learned behavior, the mariner model attempts to derive the results of the learned behavior by analytical methods. The mariner model utilizes those LOP pairs which are expected to produce the smallest measurement errors. It was expected that this analysis technique would replicate the mariner's actions (in terms of information used) and this can now be validated, at least in a preliminary sense.

The remainder of this subsection describes the specific analysis and computation techniques used within the model for the derivation of anticipated cross track and along track error variances.

Each line of position is based upon an observation, or measurement. Associated with each type of observation is a mariner's anticipated error variance. This variance value reflects the mariner's confidence in his ability to accurately make the particular observation. These variances are distinct from the actual error variances which are used by simulation to randomly produce observation errors. In other words, the mariner model selects observations (LOP's, and LOP pairs) based on anticipated error variances. These are not necessarily equal to the actual error variances (although equal values are currently being used) and in no case is the mariner (model) cognizant of an actual error value.

Theoretically, the anticipated observation error variances propagate into variances in the lines of position. In turn, variances in the lines of position impose variances on their

intersection. Of interest is to estimate the variance of the intersection points relative to the cross-track and along-track directions.

The observation errors are assumed to be normally distributed. The LOP equations are reasonably complex, involving various trigonometric functions. Various approximations and assumptions were necessary, as is discussed in the following paragraphs.

For variance computation purposes, the LOP's were assumed to be straight lines (tangent to the actual LOP at the vessel's true position). For each LOP, its orientation and "perpendicular variance" are computed. These were derived as follows.

Let α be the observation upon which a given LOP is based (α would be either an angle, distance, etc.). The LOP is then defined by:

$$y = f(x, \alpha)$$

This equation may or may not be solvable for y. At the true vessel location, the value of dy/dx can be found, usually by implicit differentiation. Thus, the orientation is readily determined:

$$\theta_{LOP} = \tan^{-1}(dx/dy)$$

as depicted in Figure F.4. Specific equations for the partial derivatives will not be presented since they are cumbersome and would not appear to contribute meaningfully to the current discussion.

Of interest next is to identify the perpendicular change in the LOP as a function of a change in α. The perpendicular change (Δ_{LOP}) can be expressed in terms of a change in α (Δ_α) as shown on the following page.

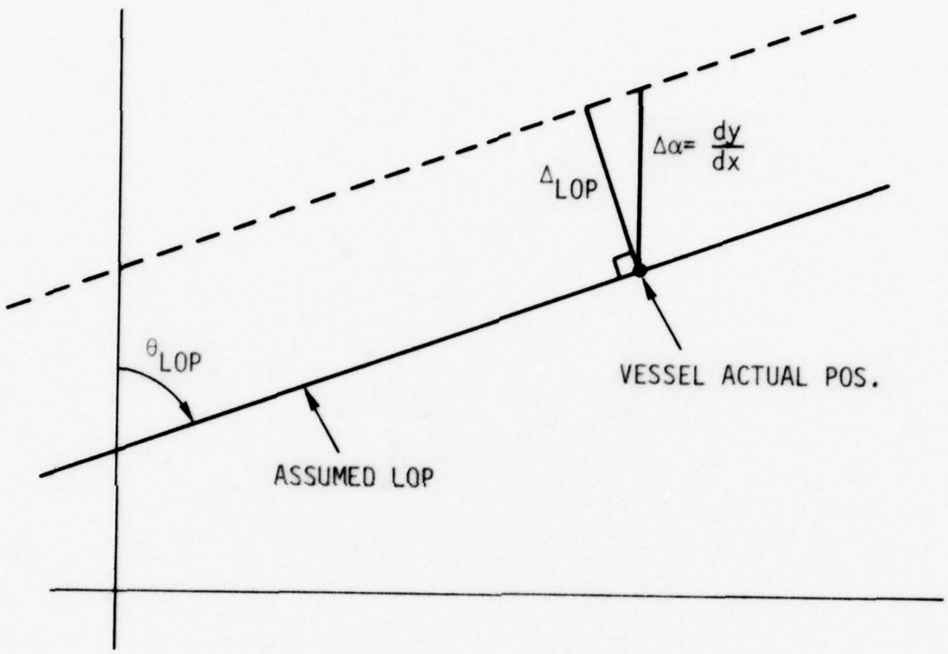


Figure F.4 Illustration of LOP Orientation
and Perpendicular Variance

$$\Delta_{LOP} = \Delta_\alpha \frac{dy}{d\alpha} \sin \theta_{LOP}$$

Assuming that $dy/d\alpha$ and θ_{LOP} are (reasonably) constant for small changes in α, then Δ_{LOP} is equal to Δ_α multiplied by a constant. The appropriate variance equation is therefore:

$$\sigma^2_{LOP} = \sigma^2_\alpha (dy/d\alpha)^2 \sin^2 \theta_{LOP}$$

where,

σ^2_{LOP} is the perpendicular LOP variance, and

σ^2_α is the anticipated error variance for the particular observation.

As before, $dy/d\alpha$ can be found via implicit differentiation, for a given vessel position. It is useful to note that the orientation can be rewritten as:

$$\theta_{LOP} = \tan^{-1} (dx/dy)$$

$$= \tan^{-1} \left(\frac{dx/d\alpha}{dy/dx}\right)$$

It then follows that the sine of the orientation can be expressed as:

$$\sin \theta_{LOP} = \frac{dx/d\alpha}{\sqrt{(dx/d\alpha)^2 + (dy/d\alpha)^2}}$$

This permits the variance equation to be re-written as follows:

$$\sigma^2_{LOP} = \frac{\sigma^2_\alpha}{(d\alpha/dx)^2 + (d\alpha/dy)^2}$$

This is a more tractable expression and was utilized in the model because it retains validity when the orientation is zero.

The orientation and variance values are computed for each LOP that appears in any of the LOP pairs to be analyzed. The next step in this part of the processing is to combine the orientations and variances for the two LOP's in each LOP pair to obtain anticipated error variances for cross track or along track position estimates. This is done as follows. First, the LOP orientations are altered so that they reflect the angle relative to the direction of interest. This is done as given below (also depicted in Figure F.5):

$$\theta_{CTD} = \theta_{LOP} - \theta + 90°$$

$$\theta_{ATD} = \theta_{LOP} - \theta$$

These revised orientations permit the construction of a new coordinate system, shown in Figure F.6. In this figure, the (true) LOP's are shown to intersect at the origin, which is the true vessel position. For the situation illustrated (cross-track variance is being computed), the X' axis is parallel to the track; Y' axis is perpendicular to the track. (The reverse is true when along track position is being considered, but the computations are identical in all other respects.)

Letting e_1 and e_2 be perpendicular LOP errors, the "observed" lines of position are given by:

$$Y' = \frac{X'}{\tan \theta_{CTD_1}} + \frac{e_1}{\sin \theta_{CTD_1}} \qquad \text{from } LOP_1$$

$$Y' = \frac{X'}{\tan \theta_{CTD_2}} + \frac{e_2}{\sin \theta_{CTD_2}} \qquad \text{from } LOP_2$$

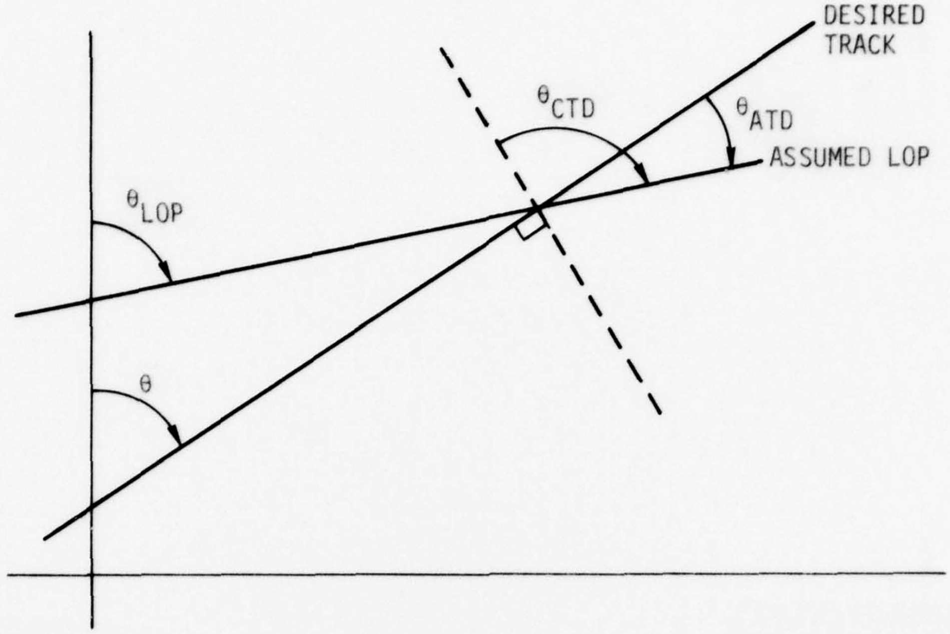


Figure F.5 LOP Orientation Relative to Cross-Track/ Along-Track Directions

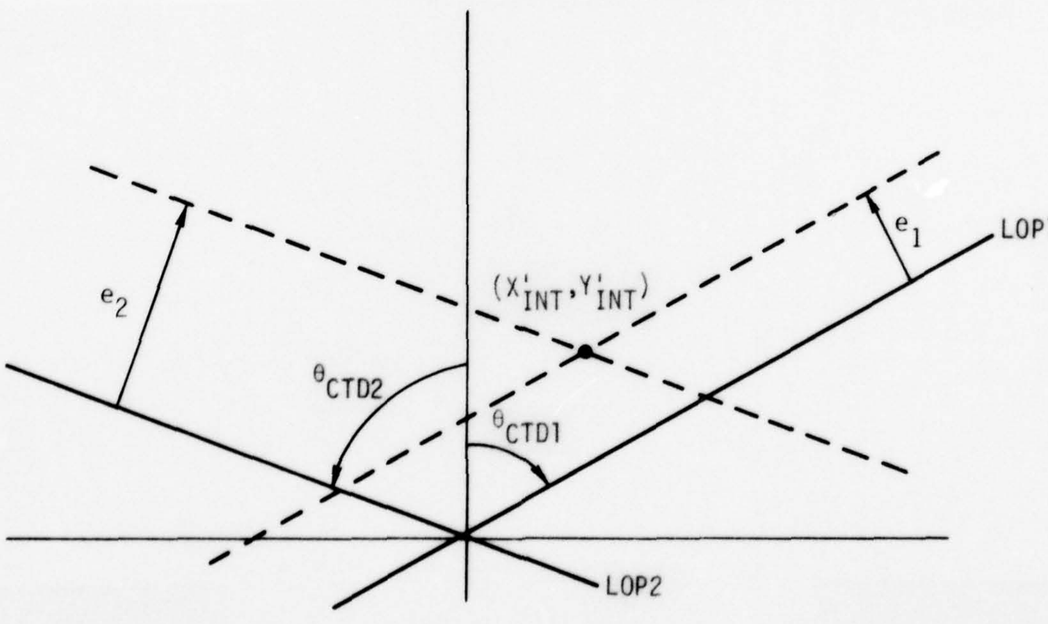


Figure F.6 Cross-Track Deviation Variance Computation

The equation prescribing the y' value of the intersections of these LOP's can be written as:

$$y'_{INT} = \frac{1}{\tan \theta_{CTD_1} - \tan \theta_{CTD_2}} \left\{ \frac{e_1}{\cos \theta_{CTD_1}} - \frac{e_2}{\cos \theta_{CTD_2}} \right\}$$

With the coordinate system as shown in Figure F.6, cross-track estimate error is equal to y'_{INT}. When both e_1 and e_2 are zero, then y'_{INT} is zero, and the cross track position estimate is perfect. Thus, the variance of y'_{INT} (about zero) is the cross track error variance. Noting that the variances of e_1 and e_2 are the perpendicular LOP variances and under the assumption that the LOP perpendicular errors are independent (which is not always the case, since they may depend upon a common observation), then the desired variance can be written as:

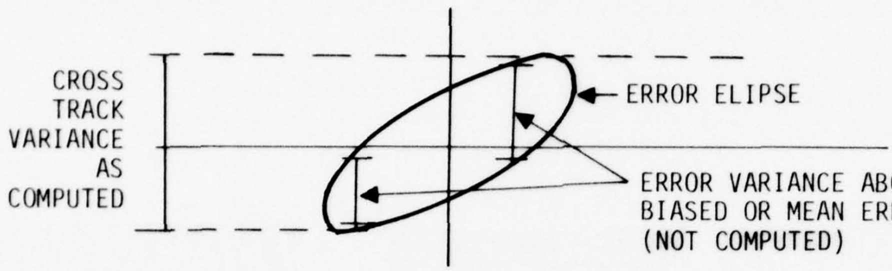
$$\sigma^2_{CTD} = \sigma^2_{y'_{INT}} = \frac{1}{(\tan \theta_{CTD_1} - \tan \theta_{CTD_2})} \cdot$$

$$\left\{ \frac{\sigma^2_{LOP_1}}{\cos^2 \theta_{CTD_1}} + \frac{\sigma^2_{LOP_2}}{\cos^2 \ {}_{CTD_2}} \right\}$$

This can be simplified to yield:

$$\sigma^2_{CTD} = \frac{\cos^2 \theta_{CTD_2} \sigma^2_{LOP_1} + \cos^2 \theta_{CTD_1} \sigma^2_{LOP_2}}{\sin^2 (\theta_{CTD_1} - \theta_{CTD_2})}$$

In light of the above derivation, the cross-track variance is computed independently of the associated or implied along-track position estimates (i.e., values of x'_{INT}). The cross-track variance is not computed as a variance about an average cross-track error value. Thus, what is being computed versus what is not computed is shown below:



Finally, prediction/dead-reckon cross-track and along-track estimates are also utilized. These are formed as follows:

$$CTD_{DR,t} = \hat{CTD}_{FINAL,t-1} + \Delta t \; \hat{\dot{CTD}}_{FINAL,t-1}$$

The anticipated variance is given by

$$\sigma^2_{CTD_{DR,t}} = \sigma^2_{\hat{CTD}_{FINAL,t-1}} + \Delta t^2 \; \sigma^2_{\hat{\dot{CTD}}_{FINAL,t-1}}$$

Similar equations are used for along-track estimates.

Rudder Position

Rudder position information is assumed to be obtained only from the rudder indicator, and the capability to consider rudder indicator errors is incorporated into the model. In the current version of the model, however, the decision and control submodels do not explicitly utilize rudder position information.

F.2.1.1.4 Weighting factors and the combining of redundant (multiple) estimates

The preceding subsection described which information is utilized for the primary, secondary and dead-reckoning estimates for each state. Subsequent to the actual generation of observations and resulting state estimates (which is described in the next subsection), the estimates must be combined to form "final" state estimates. As has been mentioned, this is done by taking a weighted average of the primary, secondary and dead-reckoning estimates. The weights are selected so as to produce a final estimate with minimum (anticipated) variance. This degree of optimality is considered appropriate when attempting to mimic the performance of a trained mariner. Computation of the anticipated variance of the final (combined) estimates is also performed. These results are utilized to derive suitable error variances (i.e., weights) of the dead-reckon estimates for the subsequent time period.

For all of the states, the primary, secondary and dead-reckoning estimates were assumed to be independent. Under this assumption, the weighting factors and the general weighted-averaging technique can be presented as follows. Let

E_1, E_2, E_{DR}	be the state estimates for a given state, obtained from the primary, secondary and "DR" sources, respectively; and
$\sigma^2_{E_1}, \sigma^2_{E_2}, \sigma^2_{E_{DR}}$	be the anticipated error variances associated with the primary, secondary and dead-reckoning estimates.

The "final" state estimate is given by

$$\hat{E} = W_1 E_1 + W_2 E_2 + W_{DR} E_{DR}$$

where

$$W_1 = \frac{1}{S\ \sigma^2_{E_1}}$$

$$W_2 = \frac{1}{S\ \sigma^2_{E_2}}$$

$$W_{DR} = \frac{1}{S\ \sigma^2_{E_{DR}}}$$

and

$$S = \frac{1}{\sigma^2_{E_1}} + \frac{1}{\sigma^2_{E_2}} + \frac{1}{\sigma^2_{E_{DR}}}$$

The anticipated variance of the final estimate is $1/S$.

F.2.1.1.5 Generation and combining of actual observations

It is appropriate to reiterate the fact that all of the preceding discussions of errors and error variances were in reference to "anticipated" variances. All "decisions" by the state estimator regarding which information to utilize are based on anticipated error variances, not actual error variances.*

At this stage of model execution, random observation errors are selected based upon the "actual" error variances. These variances are intended to reflect the mariner's ability to accurately make the observations, rather than his perception of his ability to do so. As mentioned, these variances are currently equal, but the capability exists to change either or both data

* Unless otherwise instructed by the user, the model nominally equivalences the anticipated and actual error variances.

sets if information is obtained indicating that perceived and actual capabilities are not equal or if such changes are necessary to provide proper model performance.

The generation of the random errors is straightforward. The procedures follow directly from the error models presented previously. "Bias" errors are selected at the beginning of each Monte Carlo trial. "Common" errors are selected for each time period (randomly for each trial). "Random" errors are independently selected for each individual observation. The error generation process is standard. Each actual error, denoted by e_i, is computed as follows:

$$e_i = \sigma_e \cdot x_i$$

where

σ_e is the desired error standard deviation

x_i is a random sample from a zero-mean normal distribution with standard deviation of 1.

For each of the states except cross track and along track, computation of the respective state estimate is based directly on the error models and the state estimate equations previously described. For cross track and along track, however, the intersection of the "observed" LOP's must be found. Since the LOP equations in themselves are very complex, no attempt to derive equations for their intersections was made. Alternatively, a general iterative solution procedure was developed. The procedure calls for: (a) making an initial x-coordinate estimate of observed vessel position, (b) using an explicit solution for one of the LOP's to obtain a y-coordinate value, and (c) using the x-y point thus obtained to establish a corresponding observation value for the second LOP. This observation value is then compared to the actual observation value. If they are near equal, then the x-y

point is used as the "observed" vessel position (which is then converted into a cross track or along track estimate, as appropriate). If the values are not equal, the procedure is repeated using an updated initial x-value. Standard logic is used to determine whether x should be increased or decreased, and by what amount.

The LOP intersection determination logic is not designed to include any additional error terms. The intent is to find an exact intersection of the observed LOP's. However, since the procedure is iterative, a stopping criteria must be employed. The criteria values are currently set so that the computed intersection is no more than 10 feet from its proper value.

Arguments can be made, however, that the intersection logic should include additional error terms. These are to account for the mariner's errors in "rotating" or "translating" the observations into position estimates. One way to do this is to utilize linear transformations similar to those used in the anticipated variance computations. Alternatively, random errors may simply be added to the exact x-y results. When more data and experiment results are obtained (Phase II), it will be possible to establish whether or not additional error terms are needed, and how they can be most efficiently incorporated into the model.

As mentioned, the role of the State Estimator is to provide estimates of vessel status to the Decision Maker and Commander submodels. The preceding sections described how these estimates are computed. Descriptions of the Decision Maker and Commander submodels, describing how the estimates are used, are presented in the following section.

F.2.1.2 Decision Maker

The pilot Decision Maker role consists primarily of two modes--the Monitor mode and the Controller mode. These modes are reflected

in the block diagram shown in Figure F.7. The functional steps of the Decision Maker role are listed in Table F.6. The inputs and outputs to the Decision Maker role are presented in Table F.7.

Initially, when the pilot is in the decision making role, he is comparing his estimate of the vessel state and other variables to what he knows the nominal vessel track should be. He first looks for unusual events such as the approach of another vessel, the channel boundary (e.g. sandbar), or an obstacle. If these are present he will assess his state with respect to these entities. The occurrence of one of these entities is referred to here as a "tactical" event. Such tactical events are not implemented in the Phase I model, although provision for their inclusion has been made.

If these unusual entities are not present, the pilot next compares his state to where his next change in course is. Finally, if the nominal course change is still some time off, the pilot then compares his vessel state to what he considers to be the nominal path he wishes to follow. When the pilot is assessing his state with respect to the next course change or the nominal path, he is referred to here as being a "strategic" decision maker.

The pilot's attentiveness in the decision making role is dependent upon whether he is just monitoring the vessel progress or he is actively controlling the progress. In either case, the pilot's first decision is assessing the relative error state of the vessel.

When the pilot is functioning as a Monitor, this implies that the previous estimated state of the vessel was perceived to be satisfactory. That is, the pilot previously judged the error state sufficiently small, and actual control of the vessel was being handled by the helmsman. If the pilot is monitoring progress,

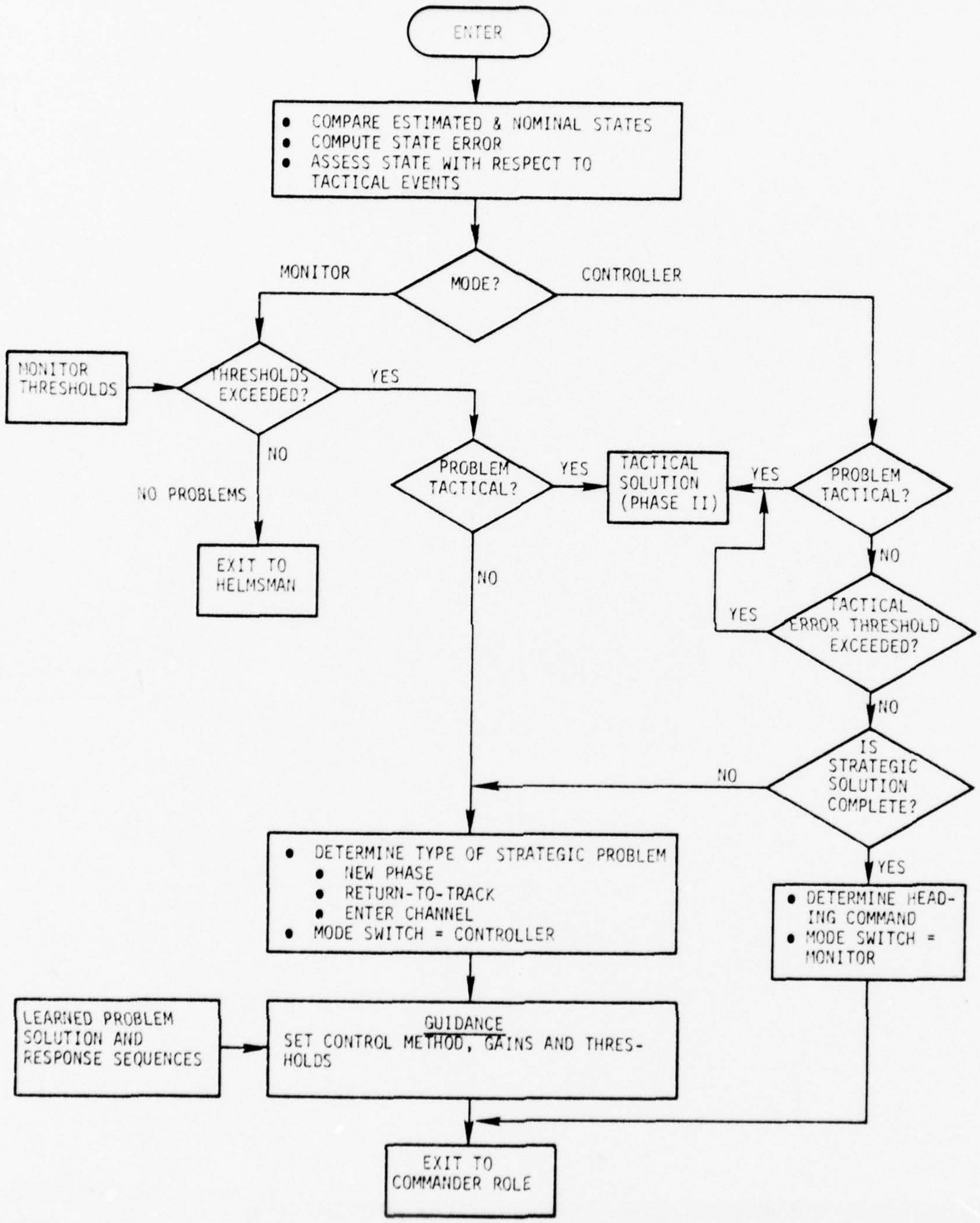


Figure F.7 Block Diagram of Pilot Decision Maker Role

Table F.6

Decision Maker Functional Steps

INITIAL

- Compare state and decision variables to nominal track
- Compute state errors
- Evaluate state with respect to other vessel, channel boundary, or obstacle (Phase II)
- Test if monitor or controller

MONITOR FUNCTION

- Test errors against monitoring thresholds
  - No problem - maintain status quo - exit to Helmsman model
  - Problem - continue
- Determine type of problem
  - Tactical - go to Tactical Solution block (Phase II)
  - Strategic - continue
- Determine type of strategic problem
  - Time-to-begin-new-phase
  - Return-to-nominal-track
  - Set mode switch to "controller"
  - Go to Guidance Function block

GUIDANCE FUNCTION

- Time-to-begin-new-phase
  - Negotiate bend
    - Compute position to start and stop rudder deflection sequence
    - Compute rudder deflection sequence
    - Compute nominal turn path
  - Enter straight segment - compute desired heading
  - Enter channel (Phase II)
- Return-to-nominal-track
  - Test errors against strategy thresholds
  - Set control law and gains
- Go to Commander Function block

CONTROLLER FUNCTION

- Determine type of problem
  - Tactical - go to Tactical Solution block (Phase II)
  - Strategic - test for tactical thresholds; if not exceeded, continue
- Test if strategic solution complete
  - Yes - determine heading command
    - set mode switch to "Monitor" - exit to Commander Function
  - No - continue
- Determine type of strategic problem
  - Negotiate bend
    - Change in sequence - determine next command; exit
    - No change - continue
  - Return-to-nominal-track
    - Test tracking thresholds
      - No problem - maintain status quo; exit
      - Problem - determine type of steering required
- Go to Commander Function

Table F.7

Pilot Decision Maker Function Inputs and Outputs

INPUTS

- Outputs from State Estimator Function
- Monitor or Controller mode
- Desired course, state, and safety margins
- Position of other vessels, channel boundaries, and obstacles (Phase II)
- Tactical problem solutions from training (Phase II)
- Strategic problem solutions from training (Guidance Function)
- Decision time delays and errors
- Pilot's knowledge of ship dynamics (response characteristics)

OUTPUTS

- Monitor/Controller mode status
- Tactical/Strategic problem status
- Control requirements (functional) and qualitative sequence
- Guidance function solutions
- Control sequence status
- Pilot attention level

he continuously assesses (with a lesser degree of attentiveness) the helmsman's performance. If the pilot perceives no problem, he continues with the status quo and the helmsman continues to function as before.

If the pilot decides that a problem exists or that a course change is required, he then decides to take over command. He switches mentally to an active "Controller" mode.

The pilot's next decision involves identifying exactly what type of vessel maneuver problem exists. Associated with each maneuver problem is a trained procedure that the pilot has learned to resolve that problem. The maneuver problems and the learned solutions can be thought of collectively as a catalog of procedures existing in the pilot's mind. This catalog is referred to as the "Guidance Function." During the decision making process, the pilot

uses the identified problem/corrective maneuver to identify the guidance procedure to follow in his subsequent Commander role.

The Phase I study has focused on two general strategic maneuver problems – negotiating bends and returning to track. In the subsequent phase, several other strategic and tactical situations will be modeled and examined.

When in the Controller mode and the maneuver is strategic, the pilot is mainly deciding how much rudder angle to command and when the next rudder command should be given. For negotiating a bend, he decides when to command that the rudder be deflected, when to reverse directions, and when the rudder should be set to zero. This is referred to in the literature as a "precognitive" function. For a return-to-track maneuver, there are three types of situations which may exist; each is discussed in the next section on Guidance.

When in a strategic Controller mode, there are three other types of decisions that the pilot may make. One is the decision that the strategic maneuver is complete. If this decision is made, the pilot decides what heading the vessel should subsequently maintain. This heading is based on the one shown on the chart of the channel, the prevailing current, the vessel speed, and the pilot's general knowledge of the channel. This heading is given to the helmsman, and the pilot then mentally switches back to the Monitor mode.

The second type of strategic decision is made when the vessel is going around a bend. Here, if the vessel drifts off the nominal track far enough, the pilot decides to add the return-to-track commands to the nominal commands used to negotiate the bend.

The third type of decision mode is when a tactical problem appears while a strategic maneuver is in progress. In this case, the pilot decides to switch to solve the tactical problem because it has higher priority. Sometimes, the tactical and strategic maneuvers are combined, such as the routine meeting of two vessels.

F.2.1.3 Guidance Functions

The guidance function of the pilot is not a normal sequence that he goes through in controlling the navigation process. Rather, it is a body of knowledge (the catalog of procedures spoken of earlier) that the pilot has in his mind. He refers to this catalog both while being a Decision Maker and a Commander.

There were two types of guidance functions modeled for the studies of Phase I - the return-to-track maneuvers and the bend negotiation maneuvers. Each of these is now explained.

First, for the return-to-track maneuver, consider three different ship orientations shown in Figure F.8 with respect to the desired course. The desired position threshold about the course is defined by the lateral distance $\pm D_1$. The distance D_2 is a lateral position outside of which the control strategy changes.

The vessel lateral dynamics can be approximated by Eq. (F.1).

$$\begin{aligned} I_s\ddot{H}_e + a\dot{H}_e &= K_sR, \\ \dot{CTD} &= VH_e \end{aligned} \qquad (F.1)$$

Here, I_s is the yaw moment of inertia, a is the lateral damping factor, K_s is the rudder effectiveness, R is the rudder angle, $\dot{CTD}$ is the distance from the desired track, V is the ship's speed, $\ddot{H}_e$ is the error in the heading angle* and

$$\dot{H}_e = \dot{H}_d - \dot{H} \qquad (F.2)$$

where $\dot{H}_d$ is the desired heading rate (zero unless in a turn). It is assumed that $\dot{H}_e$ is relatively small and V remains relatively constant.

---

*Heading error is the difference between the vessel heading and the desired heading. The desired heading includes the pilot's estimate of the appropriate (proper) crab angle.

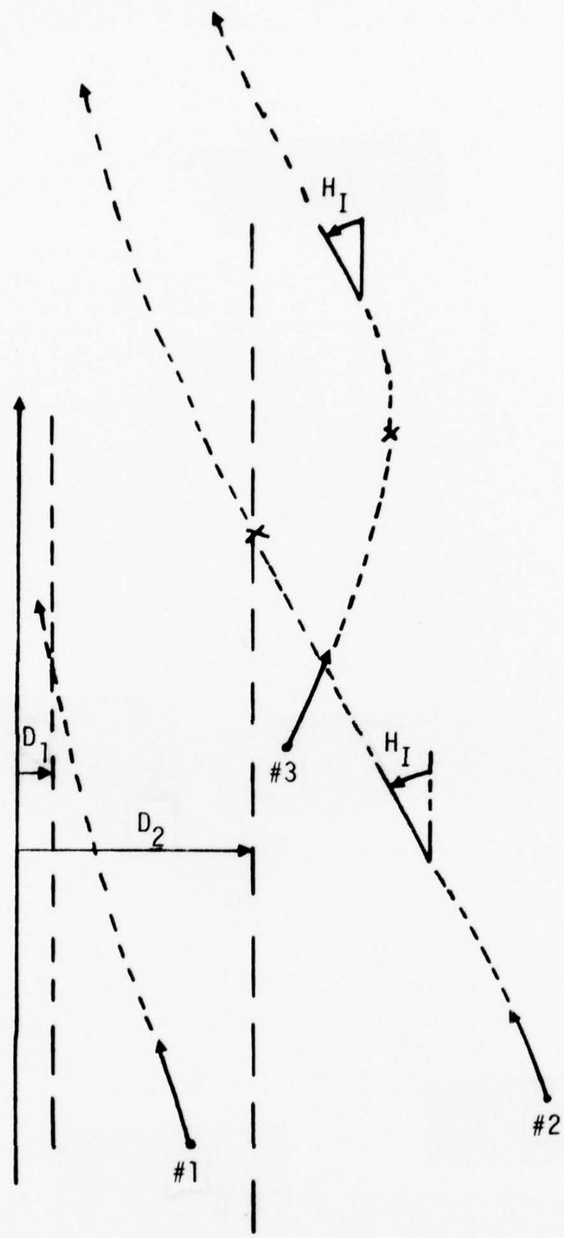


Figure F.8 Return-to-course Trajectories for Three Different Vessel Initial Conditions

Equation (F.1) is controllable. That is, a linear control law for the rudder deflection can be derived which will produce the desired return to course response.

For Vessel #1 in Figure F.8, the pilot wishes to merge the vessel into the desired track. He estimates $\hat{H}_e$, $\hat{\dot{H}}_e$, and $\widehat{CTD}$. The linear control law he then uses is

$$R_D = -K_1\hat{H}_e - K_2\hat{\dot{H}}_e - K_3\,\widehat{CTD} \qquad (F.3)$$

where

R_D is the rudder command

The pilot would quantize this rudder angle into discrete values. The gains (K_1, K_2, K_3) in Eq. (F.3) are based on the pilot's experience, his knowledge of the vessel dynamics, and the manner with which he likes to maneuver the vessel. The pilot's objective is to maneuver the vessel to within the threshold $\pm D_1$ so that subsequent control can be turned over to the helmsman for constant heading command. The manner in which he maneuvers is also governed by the pilot's uncertainty of where he is and the stress conditions he is under.

Outside of the second threshold $\pm D_2$, the pilot's objective is to return to course with a fixed intercept angle H_I*. Thus, outside of D_2, the Vessel #2 pilot will estimate the heading error H_e and compare it to the desired intercept angle H_I:

$$\hat{H}_e' = \hat{H}_e - H_I \qquad (F.4)$$

Then, he will use the control law

$$R_D = -K_4\hat{H}_e' - K_5\hat{\dot{H}}_e \qquad (F.5)$$

---

*The magnitude of the desired intercept angle H_I is a parameter of the model; the program automatically determines the appropriate sign for H_I, depending on whether the vessel is to the left or right of course.

This control strategy is maintained until the lateral error $\pm D_2$ threshold is reached. Then, the strategy is switched to that of Eq. (F.3) except that $\hat{H}_e'$ replaces $\hat{H}_e$ in that equation. Again, the rudder angle from Eq. (F.5) is quantized before being commanded to the helmsman.

When the vessel is pointed away from the desired track, as with Vessel #3 in Figure F.8, then a third strategy is used. The objective for this situation is to bring the vessel around so that its heading points the vessel back toward track, and the yaw rate is also in the correct sense. The command here is

$$R_D = \pm K_6 , \tag{F.6}$$

where the sign is determined by which side of the course line the vessel is on. After the resulting vessel orientation crosses $\hat{H}_e$ of zero, the strategy is switched to that of Eq. (F.3) or (F.5), depending on whether the vessel is inside or outside of $\pm D_2$.

Particular parameters (the gains K) to be used in the previous control laws are functions of the desired return-to-track response, vessel characteristics, and speed. Preliminary values for these parameters are derived and analyzed in Appendix H.

Now, consider the problem of negotiating a bend. It is known from considering vessel dynamics (see Section F.3) that the motion of a vessel with a fixed rudder angle can be approximated by a straight line followed by a connecting circular arc. The straight line can be thought of as a time delay; it represents the time required (after the rudder angle has been applied) before the straight line inertia of the vessel is overcome, and the vessel begins to turn.

Because a fixed rudder deflection eventually produces a nearly circular arc, a preliminary model of the command given by the pilot to negotiate a turn is a fixed rudder angle. The questions

that must be answered then are (1) how much rudder angle and (2) when to apply it, and subsequently, (3) when and how to remove it.

To obtain some information on vessel turn characteristics for bends up to 45°, Table F.8 is presented for the 80,000 ton tanker. Here, vessel speeds (V) of 6, 8, 10, and 12 kts, rudder deflections (R_D) of 2°, 4°, and 8°, and turn angles (ΔH) of 15°, 30°, and 45° are used as parameters. The consequent terms presented are the turn rate $\dot{H}$ and the turn radius of curvature. From the computed vessel dynamics, it can be seen that the turn radius of curvature is essentially independent of speed. The turn geometry appears to be solely a function of rudder angle. The turn rate is then proportional to speed. Thus, regardless of the speed, the pilot can negotiate a given bend by considering primarily the rudder angle.

Now, it is useful to consider the vessel going around a typical bend. Figure F.9 shows the 80,000 ton tanker going around the eastern bend in New York harbor's Sandy Hook channel. This is the outward bound vessel which follows the inside half of the channel. The turn geometries for rudder angles of 2°, 4°, and 8° are shown. Note the change in starting positions for the different rudder angles. Also note in Figure F.9 that a rudder angle of 10° would cause the start point to be well within the bend region. It would also cause the path followed to cross over the designated mid-channel boundary.

A rudder angle of 6° would produce about the right path for this bend. As the bend angle (B) is increased, this rudder angle would have to increase, and the start point would have to be moved upstream (closer to the origin).

For an inward bound vessel, the outside half of the channel designated in Figure F.9 could be used. As can be seen, this vessel has less maneuvering space in a passing situation. To avoid crossing

Table F.8

Parametric Values of Turn Rate and Radius of Curvature as a Function of Vessel Speed, Rudder Deflection, and Turn Angle for an 80,000 Ton Tanker

V KTS	R_D DEG	ΔH DEG	$\dot{H}$ DEG/S	RADIUS FT x 10^2	V KTS	R_D DEG	ΔH DEG	$\dot{H}$ DEG/S	RADIUS FT x 10^2
6	2	15	0.07	86	8	2	15	0.09	87
		30	0.09	66			30	0.11	66
		45	0.09	60			45	0.12	61
	4	15	0.09	65		4	15	0.12	64
		30	0.11	52			30	0.14	52
		45	0.11	49			45	0.15	49
	8	15	0.12	48		8	15	0.16	47
		30	0.14	40			30	0.18	40
		45	0.14	39			45	0.19	39

V KTS	R_D DEG	ΔH DEG	$\dot{H}$ DEG/S	RADIUS FT x 10^2	V KTS	R_D DEG	ΔH DEG	$\dot{H}$ DEG/S	RADIUS FT x 10^2
10	2	15	0.11	85	12	2	15	0.13	88
		30	0.14	67			30	0.17	67
		45	0.15	60			45	0.19	60
	4	15	0.15	65		4	15	0.18	65
		30	0.18	52			30	0.22	52
		45	0.19	49			45	0.23	49
	8	15	0.20	47		8	15	0.24	47
		30	0.23	40			30	0.28	41
		45	0.23	39			45	0.28	39

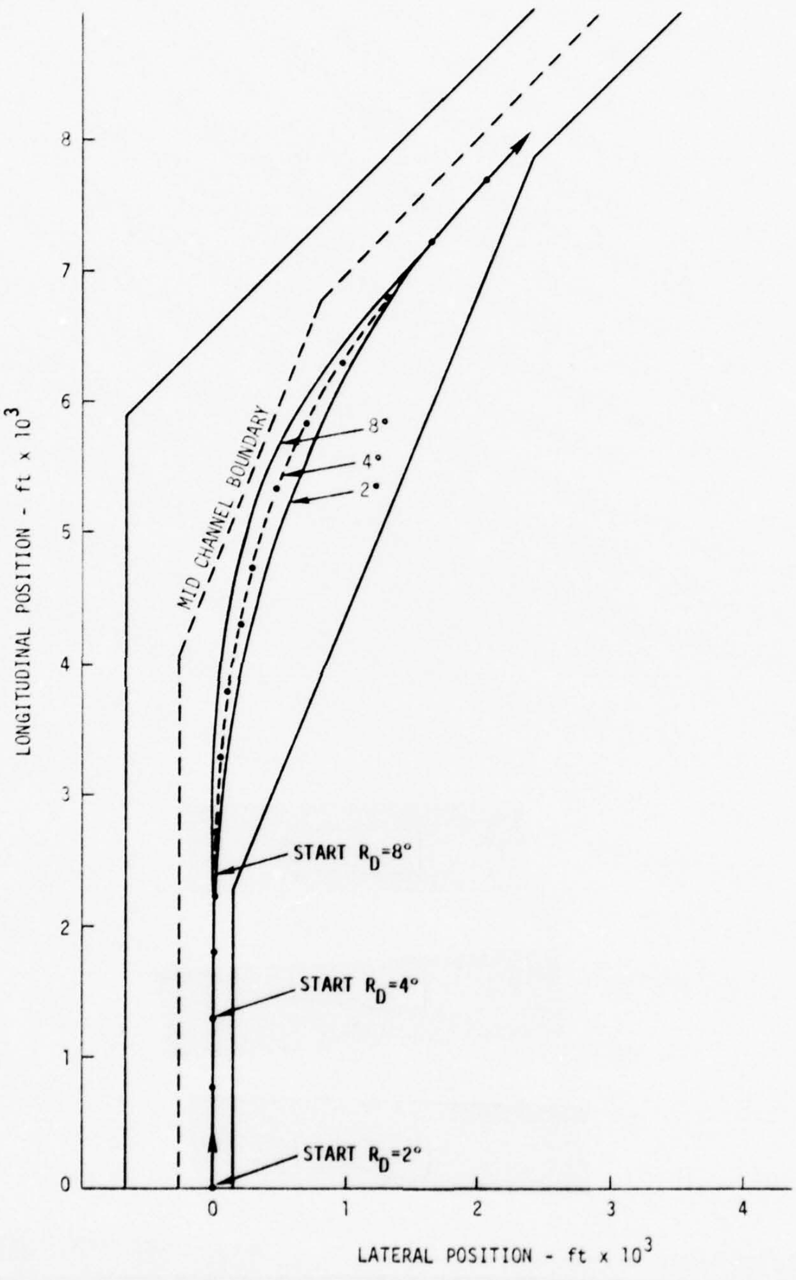


Figure F.9 Position of 80,000 Ton Tanker Rounding East Bend in Sandy Hook Channel as Function of Rudder Angle

to the inside half of the mid-channel boundary, the rudder deflection would have to be delayed and the value would have to be greater than that of the inside vessel.

Alternatively, the inside vessel could negotiate the bend in Figure F.9 with two turns of B/2 separated by a straight portion. This would require larger values of R_D. This increase in complexity would produce use of less turning space. Thus, one can see that the nominal path that a vessel follows around a bend is variable, and that to analyze aids-to-navigation requirements in a bend requires that specific turn strategies be defined.

In this study, only a single turn was considered for negotiating the bend. To determine when to apply the rudder angle and of what value, the following procedure was used. Consider the bend geometry shown in Figure F.10. Assume that the pilot has in his head a three-dimensional table for his vessel of R_D vs. ΔH vs (x,y), where (x,y) is the pair of longitudinal and lateral positions of the vessel from the point where the rudder angle was applied. Mathematically, then, the following procedure can be used to obtain the appropriate rudder angle:

(1) For a given bend, compute the equation of the final direction (line DF in Figure F.10) as it intersects the original direction (line AD in Figure F.10). This is of the form:

$$y = a_1 x + b_1 \ . \tag{D.7}$$

Here, a_1 is $\tan B$, where B is the bend angle.

(2) Also compute the equation for the outside turn boundary. This is the line CE in the example of Figure F.10 and it is of the form:

$$y = a_2 x + b_2 \ . \tag{F.8}$$

Here, a_2 is $\tan B/2$. It represents the boundary inside of which the vessel should remain during the turn.

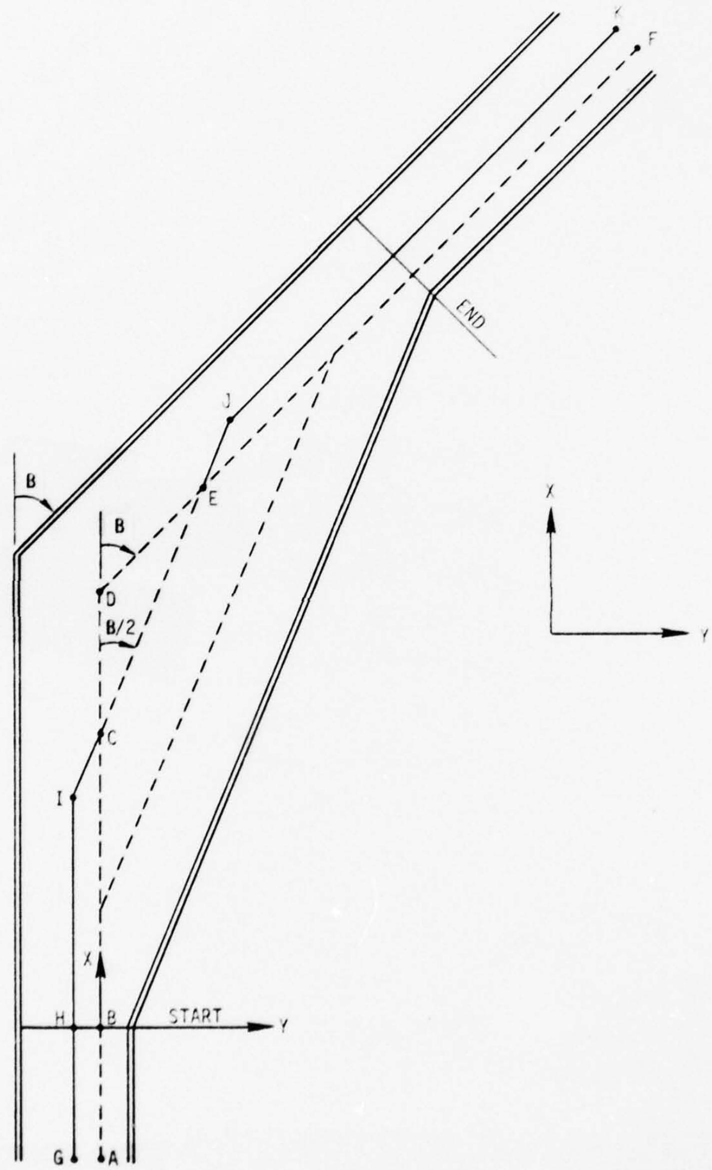


Figure F.10 Bend Restriction Geometry Details

(3) By interpolation, compute from the table, for each value of R_D, the lateral position y where the vessel is when its heading (ΔH) equals the turn angle B. Where this value of y intersects the line DF establishes one end of the turn. This should occur before the bend END point, or that particular value of R_D is too small.

(4) For the same value of R_D, next compute the (x,y) coordinates where the turn angle is B/2. This point should be on the correct side of the boundary line (CE). If this point extends over CD, the rudder angle R_D is too large, and it is rejected.

(5) Steps 3 and 4 are computed for each appropriate quantized value of R_D*. For the remaining values of R_D (that are not too large or too small), the point where the rudder angle is input can now be determined from the table (x,y) values.

(6) The single value of R_D is chosen which has a starting point closest to the START line (shown for the inside channel in Figure F.10).

The pilot does not explicitly go through the above procedure to determine what value of R_D to use and when to apply it. He knows this information based on his training and years of experience. However, the above procedure is necessary to reproduce a reasonable representation of the pilot's knowledge by simulation.

The above procedure determines R_D and when to apply it. Also, the resulting path is defined as the nominal course around the bend. The table then is used to compute the nominal value of lateral position and heading angle as a function of longitudinal position from where the rudder angle was applied. These values (y, ΔH) vs (x) are used to determine if the vessel is close enough to the nominal path during the negotiation of the turn.

*Currently, rudder commands for bend negotiation are quantized in five degree increments.

F.2.1.4 Commander

The functional steps that the pilot takes in the Commander role are listed in Table F.9. The inputs and outputs associated with this role are given in Table F.10. The Commander's role is the active portion of the pilot model. Basically, here the decisions have been made as to what the pilot must do. The Commander role is then the actions taken by the pilot, usually in the form of verbal commands, to enact these decisions.

When a maneuver is required, the Commander role refers to the Guidance Function catalog. As each maneuver progresses, the Commander issues the rudder command sequence from the catalog as deemed appropriate. If a return-to-track maneuver is being enacted, the commands consist of a series of rudder angles which will cause the vessel to merge into the threshold D_1 around the nominal path. If a bend is being negotiated, the commands will consist first of a rudder deflection to begin the turn, and then a setting of the rudder deflection in the opposite direction to stop the turn. When both of these strategic maneuvers are finished, the Commander will issue a heading command for the helmsman to hold.

The Commander role would also normally control the speed of the vessel either directly or by commands to the engine room, a function not currently implemented in the Phase I model. In close quarters, the speed is reduced to allow more time for the maneuvers. If there is a high cross current, the speed may be increased to reduce the resultant crab angle. Vessel speed control will be investigated in Phase II.

F.2.2 Helmsman

The mathematical model of the helmsman is illustrated by the block diagram shown in Figure F.11. Also illustrated in Figure F.11 is the steering gear model.

Table F.9

Commander Functional Steps

- Determine type of problem
  - Tactical - go to Tactical Command block (Phase II)
  - Strategic - continue
- Test if strategic solution complete
  - Yes - issue heading command
  - No - continue
- Determine strategic problem status
  - Status quo - exit
  - Negotiate bend sequence change - issue next rudder command
  - Enter new straight segment - issue heading command
  - Return-to-track - issue control law commands for rudder
- Go to Helmsman block

Table F.10

Pilot Commander Function Inputs and Outputs

INPUTS

- Outputs from Decision Maker Function
- Control time delays
- Control errors and command granularity
- Maneuver characteristics from the Guidance Function

OUTPUTS

- Rudder commands
- Desired heading
- Throttle setting (Phase II)

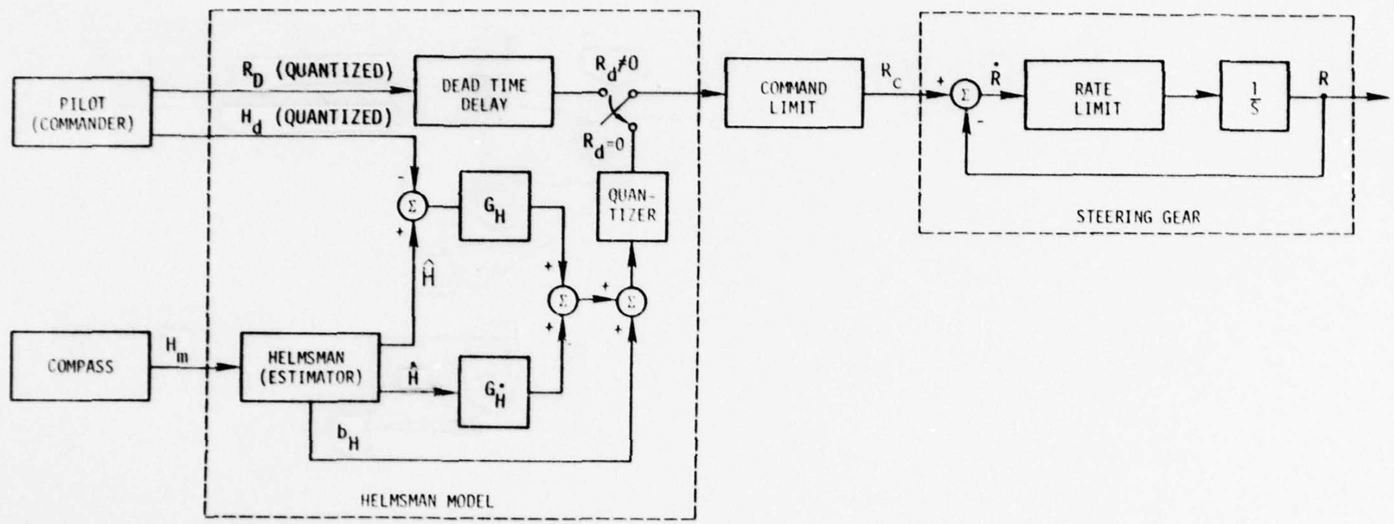


Figure F.11 Block Diagram of Helmsman and Steering Gear Models

When the pilot is in an active Controller role, he issues rudder commands R_d directly to the helmsman. After a small time delay, the helmsman inputs these commands directly to the helm. These commands are physically limited by the command limit of the helm.

When the pilot is in a passive Monitor role, he will have issued a steady heading H_d that he wishes the helmsman to follow. In this case, the helmsman must generate his own rudder deflection commands. The helmsman's chief source of information is the ship's compass with its measured heading $\hat{h}$. From this measurement, the helmsman estimates both the ship's heading $\hat{H}$ and heading rate $\hat{\dot{H}}$. The helmsman will produce some bias b_H in his estimate of $\hat{H}$ due to factors such as compass error.

In some ship bridge systems, the pilot is given an instrument reading of the vessel yaw rate. Also, in conditions of good visibility, the helmsman can estimate the vessel turn rate by watching the movement of background terrain. For this Phase I study, the estimates of $\hat{H}$ and $\hat{\dot{H}}$ were obtained in the same way as was done for the pilot (i.e. it was assumed that the two estimates were identical).

The helmsman determines the difference between the desired and estimated vessel headings. He uses this difference plus the heading rate to formulate a control law of the form

$$R_d = G_H(\hat{H}-H_d) + G_{\dot{H}}\hat{\dot{H}}. \qquad \text{(F.9)}$$

To this value is added a bias term b_H to account for instrument or rudder actuator mechanical off-sets. The rudder angle is again limited by the physical stops of the helm.

The steering gear is not a part of the helmsman model, but it is illustrated in Figure F.11 because it affects the actual rudder angle R that steers the vessel. In this gearing, a rudder angle rate is computed based upon the difference between the input and actual rudder angles. The model function is as given on the following page.

$$\dot{R} = \frac{1}{\tau_R} (R_c - R)$$

where τ_R is the rudder time constant. The function will yield a non-constant rudder turning rate. Steering gear is also characterized by a maximum achievable slewing rate. Consequently, $\dot{R}$ is limited to the range $\pm\dot{R}_{LIM}$ (nominally 2.33 deg/sec) before integration. This rate, $\dot{R}$, is then integrated to obtain the actual rudder angle.

F.3 MODEL DETAILS – NON-HUMAN ELEMENTS

The non-human elements which make up the Process of Navigation model depicted in Figure F.1 are listed comprehensively in Table F.11. The categories include the vessel, the external aids to navigation, the on board sensors, the vessel rudder and throttle, environmental effects, the harbor geometry, and other miscellaneous inputs that contribute to the process of navigation. These categories are defined in more detail in this section. Not all of the tabulated effects are included in the Phase I model: the specific models used in this study are delineated below.

F.3.1 Vessel Characteristics

F.3.1.1 Model Form

Many possible forms exist for modeling vessel dynamics. These range from ad hoc geometry-based algebraic equations to highly sophisticated, six degree-of-freedom differential equations with hull shape effects included. The form used

Table F.11

Non-Human Model Elements

Category	Elements
Vessel	Dynamic equations Hydrodynamic coefficients Shallow water effects Loading effects Wind and aerodynamic effects Vessel dimensions; wheel house location Engine characteristics
Aid to Navigation	Geometric locations and dimensions Types of navigation information Error sources and equations
On Board Sensors	Types and associated information Error sources and equations
Rudder and Throttle	Equations and coefficients
Environmental Effects	Current Wind Sea state Precipitation Cloud cover Time of day
Harbor geometry	Channel elements - bends; straight passage; entrance; anchorage Shoreline features Obstacles - bridges; sunken vessel, sand bar Depth geometry
Miscellaneous Elements	Charts Inter-vessel communication Traffic and weather advisories Rules and regulations Local custom Other vessels and their relative motion

for the vessel dynamics model lies between these extremes. It is characterized by:

(1) three degree-of-freedom motion (yaw, sway, surge), represented by three non-linear differential equations; and

(2) truncated Taylor series expansion of the hydrodynamic forcing functions, retaining only those terms which are of significance in describing vessel motion in shallow waters.

This form was selected for the following reasons:

(1) It is computationally efficient

(2) It provides an accurate representation of the vessel's motion, particularly where pitching motions are minimal.

(3) Its structure is directly expandable to include additional effects (bank suction, etc.). Such expansion would normally take the form of additional terms in the Taylor series expansion of the hydrodynamic terms and changes to the polynomial coefficients.

The differential equations describing vessel motion are written with respect to a reference frame which is aligned with the vessel's axes and centered at the vessel's center of mass, as shown in Figure F.12. Neglecting the rolling, pitching, and heaving degrees of freedom, the vessel equations of motion are:

$$\begin{aligned} m\,(\dot{u} - rv) &= X, && \text{(surge)} \\ m\,(\dot{v} - ru) &= Y, && \text{(sway)} \\ I_z\dot{r} &= N, && \text{(yaw)} \end{aligned} \qquad \text{(F.10)}$$

where

M is the effective vessel mass,

I_z is the effective vessel moment of inertia about the vertical axis,

u,v are the x-axis and y-axis components of the velocity of the vessel center of mass, and

r is the yaw rate.

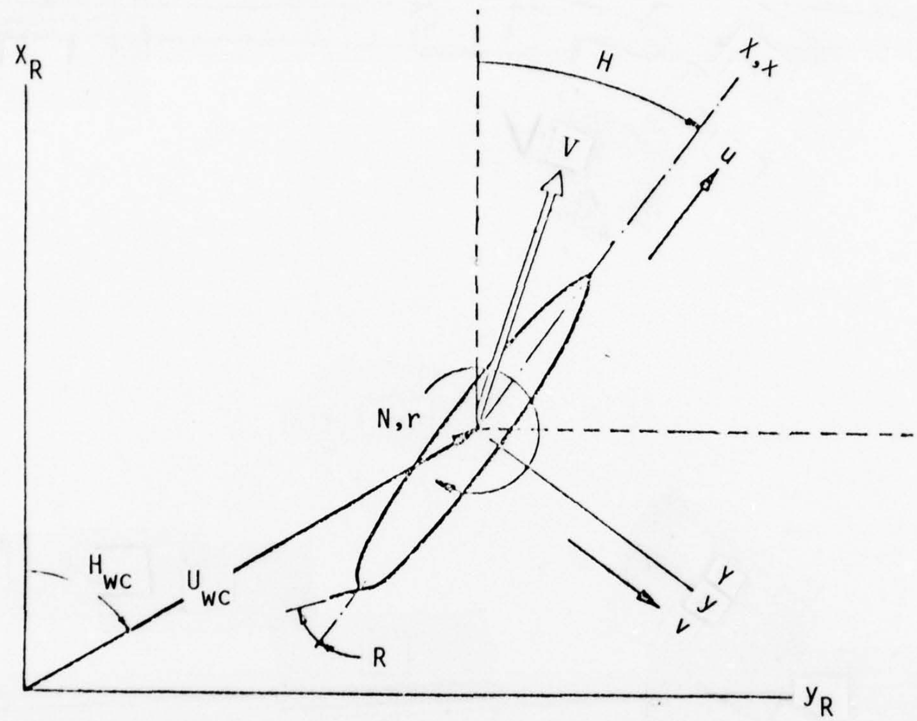


Figure F.12 Reference Frames

The X, Y and N terms in Eq. (F.10) represent the unbalanced external forces and moments applied to the vessel. These terms, which arise from hydrodynamic reactions to hull motion, propeller and rudder actions, and aerodynamic forces, are discussed shortly.

Given appropriate expressions for X, Y and N, Eq. (F.10) is integrated in the vessel coordinate frame to obtain u, v and r. The vessel velocity components u and v are then rotated to the reference (inertial) frame, where they are integrated again in order to describe the vessel's position history. A uniform water current velocity which acts at an angle H_{wc} with respect to the

reference x axis is then added. The final form of the differential equations becomes:

$$\dot{X}_R = u \cos H - v \sin H + U_{wc} \cos H_{wc}$$
$$\dot{Y}_R = u \sin H + v \cos H + U_{wc} \sin H_{wc} \qquad (F.11)$$
$$\dot{H} = r$$

Eqs. (F.10 and F.11) comprise the vessel dynamics model.

The external forces and moments (X,Y,N) which drive the vessel dynamic model are many and varied. Consequently, there is much opportunity to simplify the mathematical representations of these driving terms.

These forces and moments are considered to be of three basic types--hydrodynamic, propulsive, and aerodynamic. Each forcing function can be written as the sum of three components:

$$X = X_H + X_P + X_A \quad ,$$
$$Y = Y_H + Y_P + Y_A \quad , \qquad (F.12)$$
$$N = N_H + N_P + N_A \quad ,$$

where the subscripts H, P, and A stand for "hydrodynamics," "propulsive," and "aerodynamics" terms, respectively.

Hydrodynamic terms are represented by Taylor series expansions of X, Y, and N with respect to the variables u, $\dot{u}$, v, $\dot{v}$, r, $\dot{r}$, and R, the rudder angle. Fourth-order terms are usually neglected in the expansions. Terms retained as being significant are:

$$X \cong X_{\dot{u}}\dot{u} + X_u u + X_{rv} + X_{RR}R^2 + X_o \quad ,$$
$$Y \cong Y_{\dot{v}}\dot{v} + Y_v v + Y_r r + Y_{rvv} rv^2 + Y_{vvv}v^3 + Y_R R + Y_{RRR}R^3 \qquad (F.13)$$
$$N \cong N_{\dot{r}}\dot{r} + N_v v + N_r r + N_{rvv} rv^2 + N_{vvv}v^3 + N_R R + N_{RRR}R^3$$

where the X_i, Y_i, and N_i terms are the hydrodynamic coefficients.

The hydrodynamic coefficients are experimentally determined, and the conditions under which such experiments were conducted determine the range within which the coefficients are valid. As a result, it is important that the coefficients used in the PON model represent data collected from shallow water tests.

Restricted channel effects (bank suction, etc.) can be added to Equations (F.13) directly as polynomial terms. The coefficients for the terms are, again, experimentally derived. Due to the unavailability of data, restricted channel effects are not included in Phase I.

Standard procedure for incorporating propeller effects into the vessel dynamics is by modifying the coefficients of the R-terms in the external force and moment Eqs. (F.13). Again, the coefficients are empirically derived. An example empirical formula is:

$$Y_R = \frac{(1 + K\ S^{1.5})}{(1 + K\ S_e^{1.5})} (Y_R)_e \qquad \text{(F.14)}$$

Similar expressions are used for Y_{RRR}, N_R, *and* X_{RR}. *In these* expressions the subscript 'e' refers to equilibrium conditions and

K is an empirically derived constant,

S is the propeller slip ($1=U/pn$),

p is the propeller pitch, and

n is the propeller revolutions per second.

Propulsive control is not utilized for Phase I. Consequently, non-steady propeller effects were not included in the model at this time. In actuality, temporary bursts of propeller RPM are used as a quick-response course changer (kick-over) at low speeds. This phenomenon will be included for Phase II. The effects of bow thrusters were not included, as these are ineffective above about four knots.

Aerodynamic effects depend on the effective profile presented to wind forces; this effective profile, in turn, is a function of vessel shape, orientation, and loading conditions. In Phase II, these effects will be included in a simplified manner.

Table F.12 identifies vessel data (including appropriate hydrodynamic coefficients) currently implemented in SCI (Vt) simulations. These data were adequate for initial model development; however, additional data will be required to ensure the comprehensiveness of ship handling qualities desired. A good amount of these data are available in the literature.

Table F.12

Data Currently Implemented in SCI (Vt) Simulations

VESSEL	TONNAGE	DEEP WATER HYDRO DATA	SHALLOW WATER HYDRO DATA	CHANNEL RESTRICTION EFFECTS	PROPULSION EFFECTS
Mariner Class Cargo Ship	19,000	✓			
Tanker	80,000	✓			
American Lancer Container Ship	80,000	✓	✓		✓
Sea-Land McLean Container Ship	80,000	✓			

F.3.1.2 Vessel Dynamic Characteristics of the 80,000 Ton Tanker

A digital computer subroutine was developed using the previous equations to simulate ship motion for a variety of assumed inputs of rudder and throttle. The hydrodynamic coefficients of the 80,000 ton tanker were used for this investigation.

The simulation was first used to study the motion of the ship initially going straight forward ($v, r=0$) caused by a fixed rudder deflection. This motion is characterized by the position, forward speed, heading, heading rate, and radius of curvature of the ship's path. This information was required so that the ship's motion could be characterized qualitatively and quantitatively in simple terms and tables, and so that the response of the vessel to normal control inputs could also be described.

The motion of the 80,000 ton vessel to various rudder deflections is depicted in Figures F.13a-F.13f. The speed is initially 8 kts. Figure F.13a shows the inertial position of the vessel is traveling along the vertical axis of the plot, and it is at the origin at the initial point in time. The motion starts as a straight segment, and it is followed by a gradual turning into a final arc. As can be seen in Figure F.13a, the position is nearly a straight line path followed by a circular arc. Thus, the motion can be described as a time delay followed by circular motion (modeling simplifications of this form, however, were not made). For the path followed with a 20° rudder deflection, the time delay is about 50 seconds.

Figures F.13b and F.13c show the heading (or yaw) rate and heading angle vs. time, again as a function of rudder angle deflection. As can be seen, for a given deflection, the heading rate approaches a steady-state value with a damped second-order transient response. The steady-state value is not proportional to the rudder angle (e.g., for this vessel, an 8° deflection causes about twice the steady heading rate at a 2° deflection). Also, the

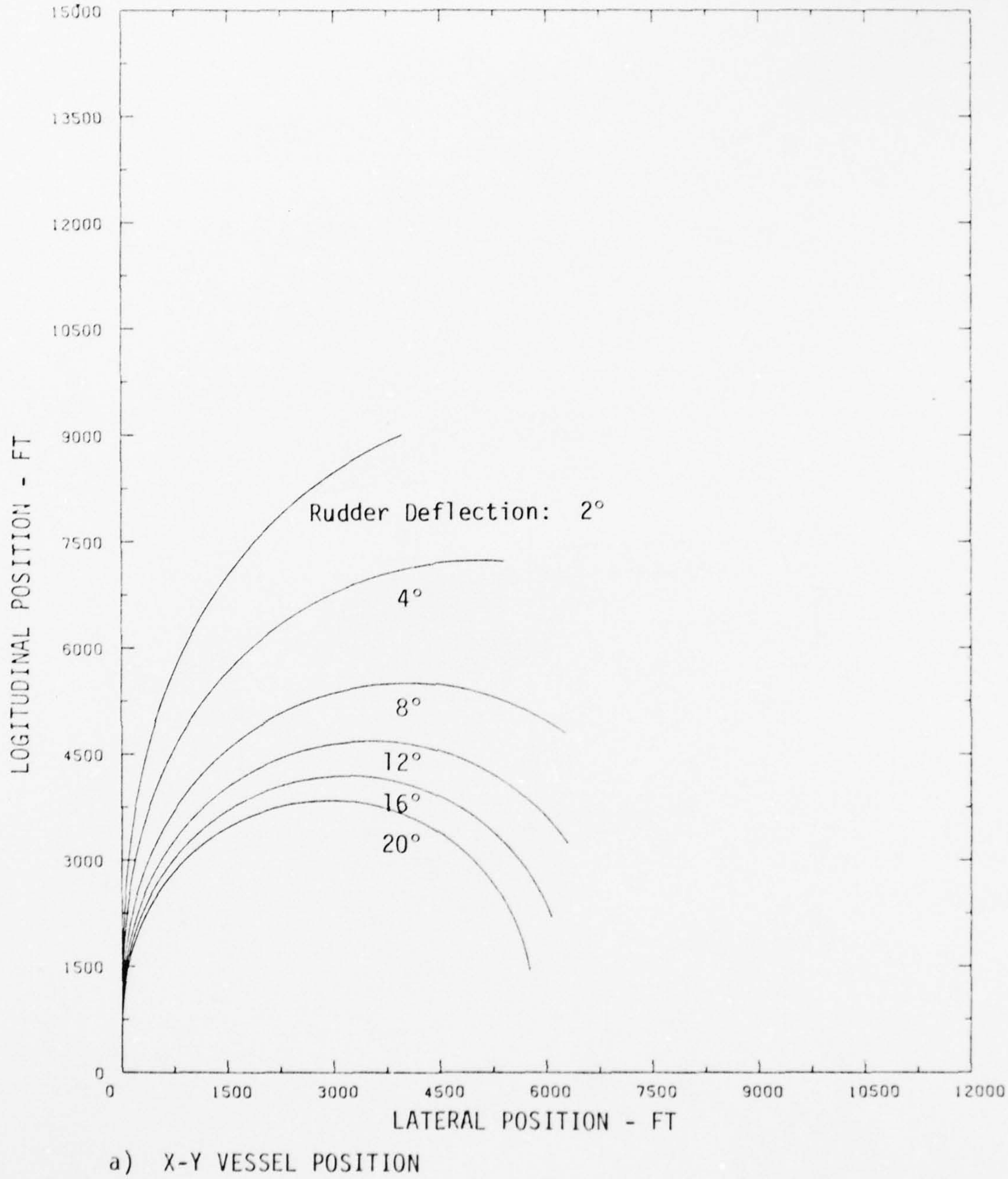
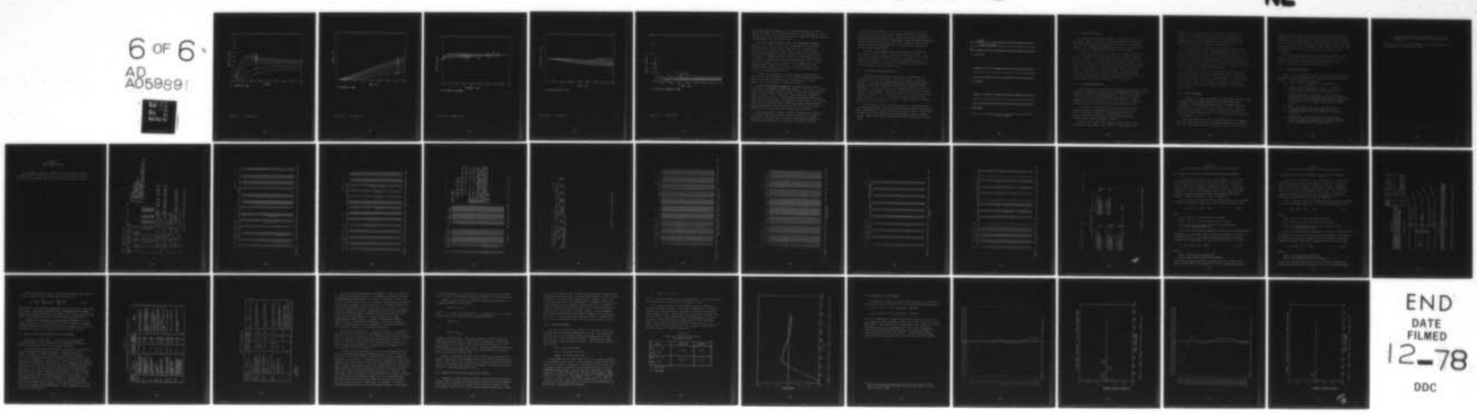


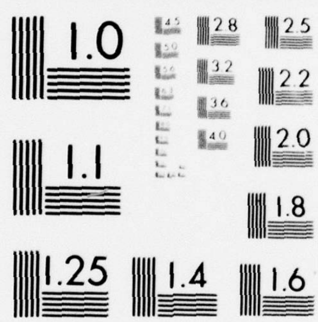
Figure F.13. Plots of 80,000 Ton Tanker Turning Characteristics as a Function of Rudder Angle for an Initial Speed of 8 Kts.

AD-A059 891 SYSTEMS CONTROL INC PALO ALTO CALIF F/G 17/7
STUDY OF THE PERFORMANCE OF AIDS TO NAVIGATION SYSTEMS. PHASE I--ETC(U)
MAR 78 W H CLARK, A R STEPHENSON, R H BATESON DOT-CG-75400-A
UNCLASSIFIED USCG-D-38-78 NL

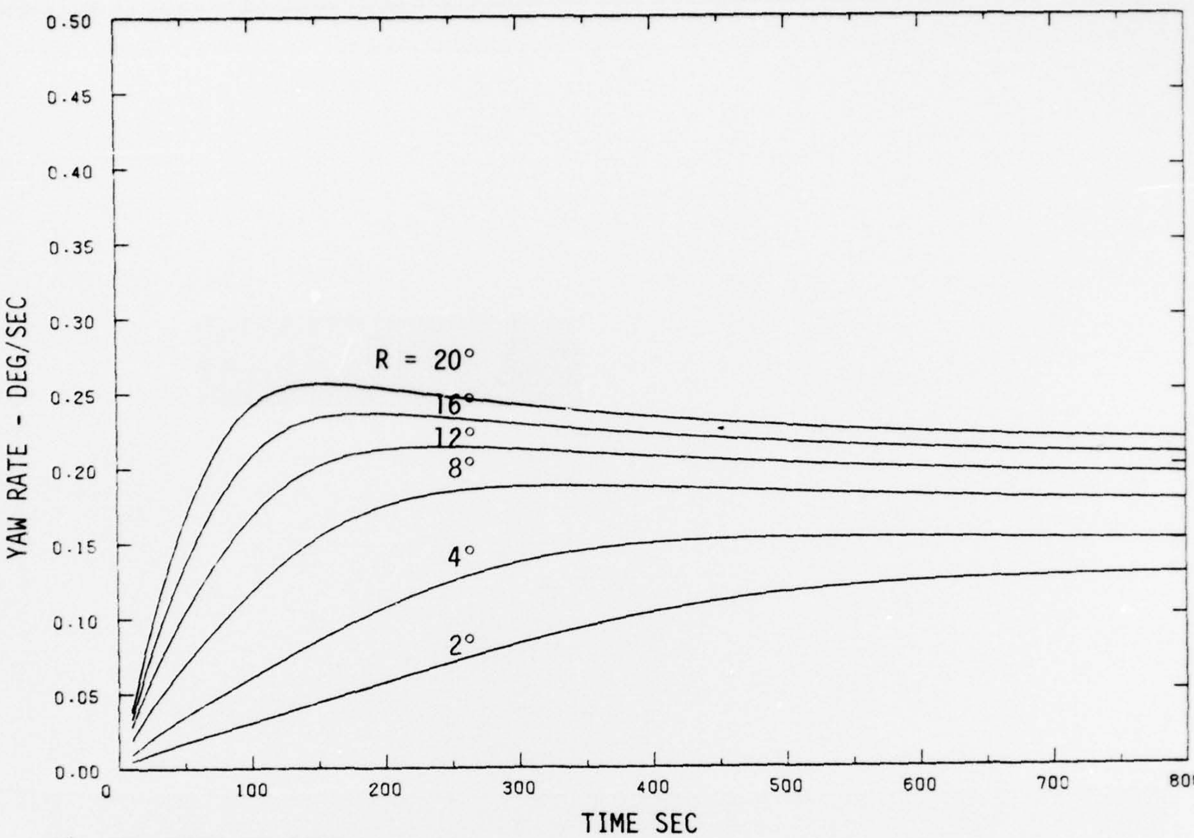
6 OF 6
AD
A059891



END
DATE
FILMED
12-78
DDC

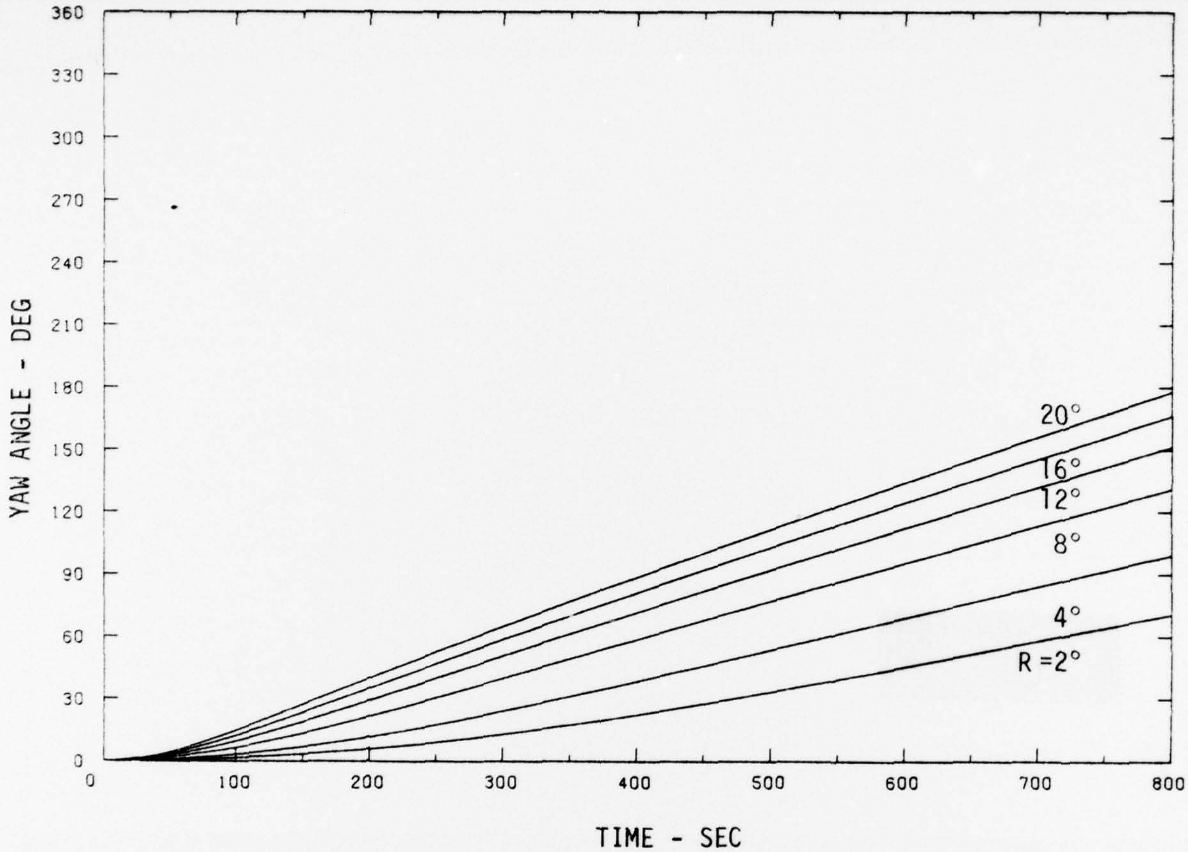


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



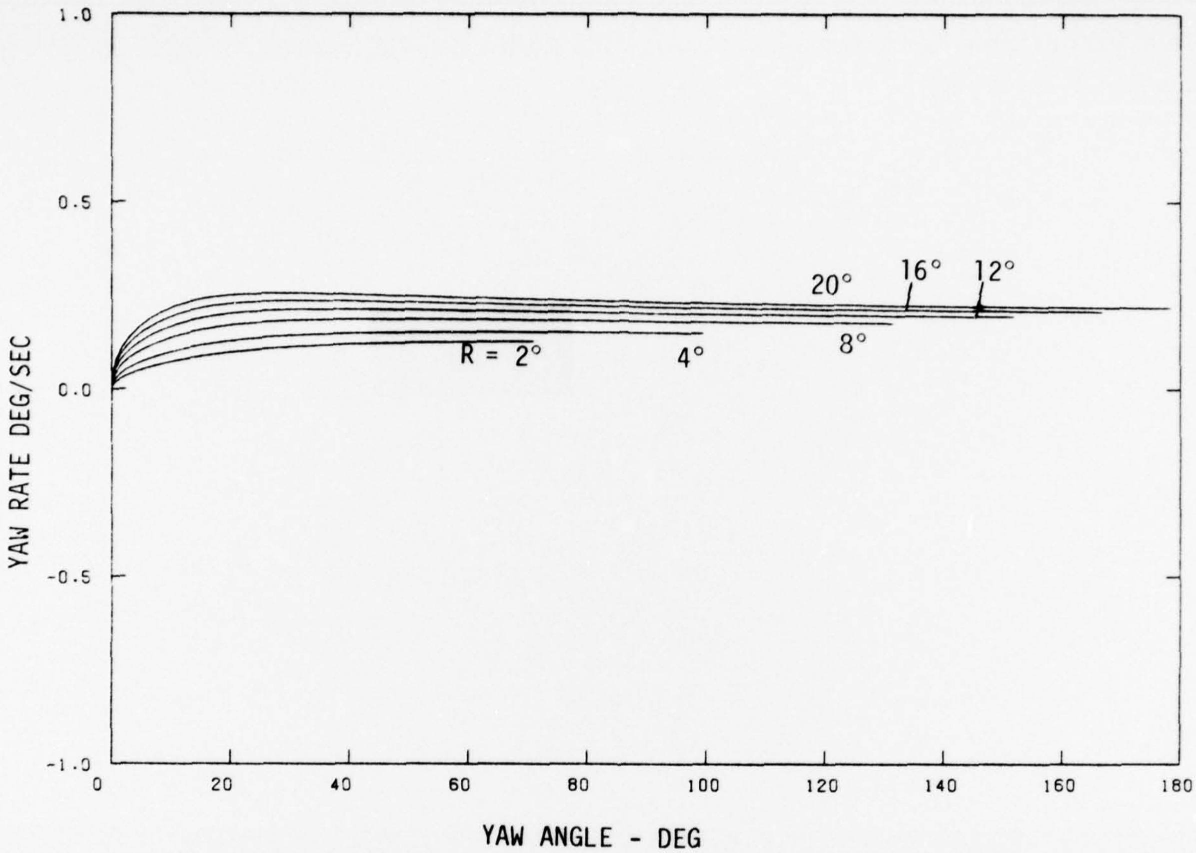
b) YAW RATE VS TIME

Figure F.13 - (Continued).



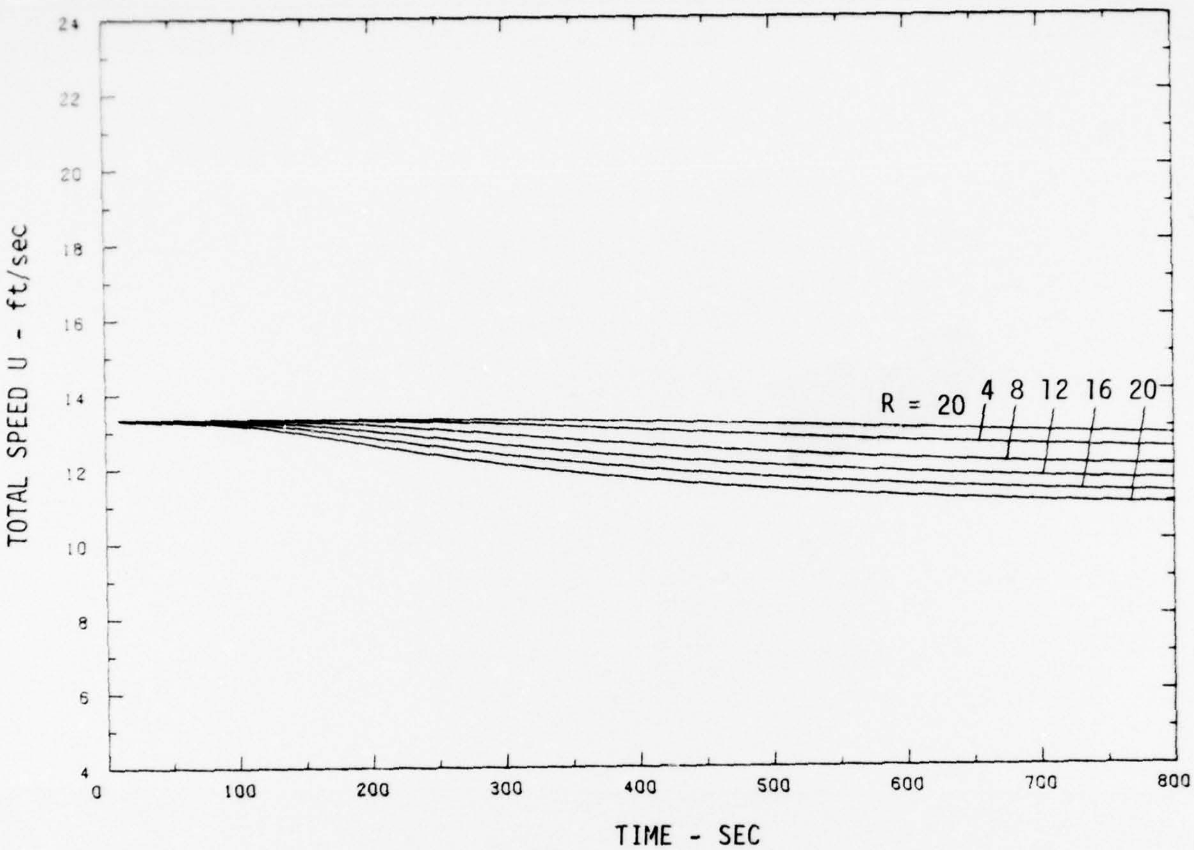
c) YAW ANGLE VS TIME

Figure F.13 - (Continued).



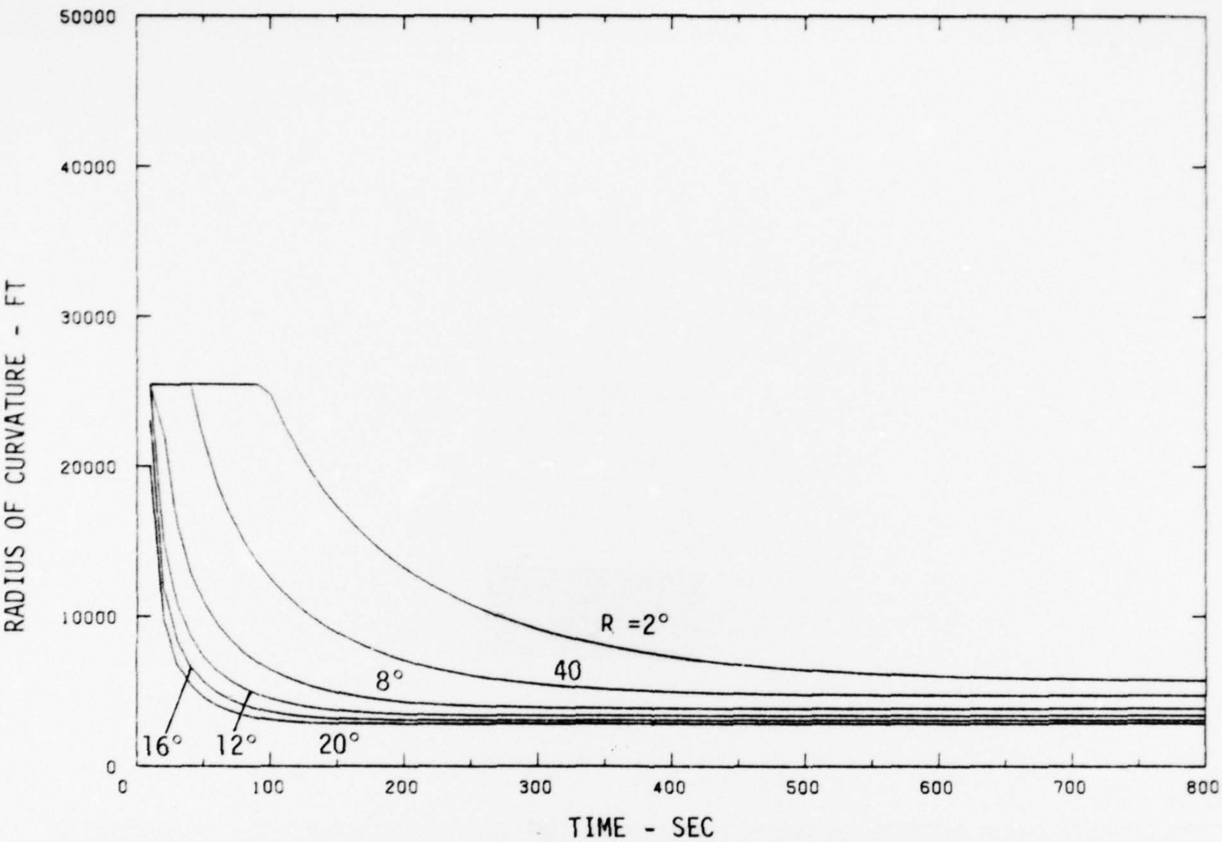
d) YAW RATE VS YAW ANGLE

Figure F.13 - (Continued)



e) SPEED REDUCTION VS TIME

Figure F.13 - (Continued)



f) RADIUS OF CURVATURE VS TIME

Figure F.13 - (Continued)

transient damping decreases as the rudder deflection increases. Thus, the effects of the nonlinearities in the equations of motion are very evident, with respect to both the speed of response and the steady-state value of the turn rate.

As can be seen in Figure F.13c, the yaw angle eventually changes at a linear rate in time corresponding to the heading rate reaching a steady value. The yaw rate is plotted as a function of yaw angle in Figure F.13d. This plot is useful in determining how far into the turn the vessel advances before it achieves a steady turn rate. Thus, for a 20^{o} deflection of the rudder, a steady turn rate is achieved after 20^{o} of a bend. On the other hand, for a 2^{o} deflection, a steady rate is not achieved until almost 90^{o} of turn. This indicates why the rudder control action usually consists of large rudder deflections for short periods of time.

Figure F.13e indicates the drop in vessel total speed as a result of the turn maneuver. A 20^{o} rudder deflection produces about a 10% drop in speed for this initial value of 8 kts. Again, this term reaches a steady state value.

Figure F.13f shows the radius of curvature of the vessel's motion for the different rudder deflections. This term is obtained by dividing the speed shown in Figure F.13e by the heading rate shown in Figure F.13b. This plot, along with the information shown in Figure F.13a, is very useful in determining what rudder angle the pilot will choose to negotiate a given bend. These plots also indicate how much lead time the pilot must allow when negotiating the bend to ensure that that vessel is turning at the appropriate rate when the vessel enters into the bend.

Refer now, back to Table F.8, where the radius of curvature is presented for four different initial speeds of the 80,000 ton vessel. From this data it can be seen that the radius of curvature does not vary as a function of yaw angle from one

initial speed to another. Thus, it can be concluded that the vessel's position subsequent to a rudder deflection is primarily a function of rudder angle only. The initial speed only affects the rate at which the turn is negotiated. Thus, the data presented for the 80,000 ton vessel at 8 kts can be used for other initial speeds in choosing the appropriate steering angle to negotiate various bend configurations.

For the present study, focus was placed on the process of navigating straight channels and bends as marked by buoys. The buoy configurations considered are shown in Figure F.14. These include the gated pairs, the staggered arrangement, and the one-sided configuration. The Process of Navigation model, however, can accommodate any buoy configuration.

F.3.3 On Board Sensors and Devices

On board sensors which are significant to the Process of Navigation include true and relative motion radars, collision avoidance systems, water depth indicators, speed log, gyrocompass, pelorus, rudder angle indicator, rate-of-turn indicator, RPM indicator, thruster (bow and stern) output indicators, and bridge communication equipment. Hand held equipment include the sextant, compass, and binoculars. Navigation charts are closely associated with these devices. Also the receivers associated with Loran, Omega, Decca, and satellite navigation systems would be considered part of the on board devices.

For the Phase I study, the three devices of concern were the ship-fixed gyrocompass, the rudder angle indicator and the speed log. These instruments are subject to bias and noise errors. Also, there is some lag in the response of the gyrocompass to ship's motion. However, these errors are insignificant for the objectives of this study.

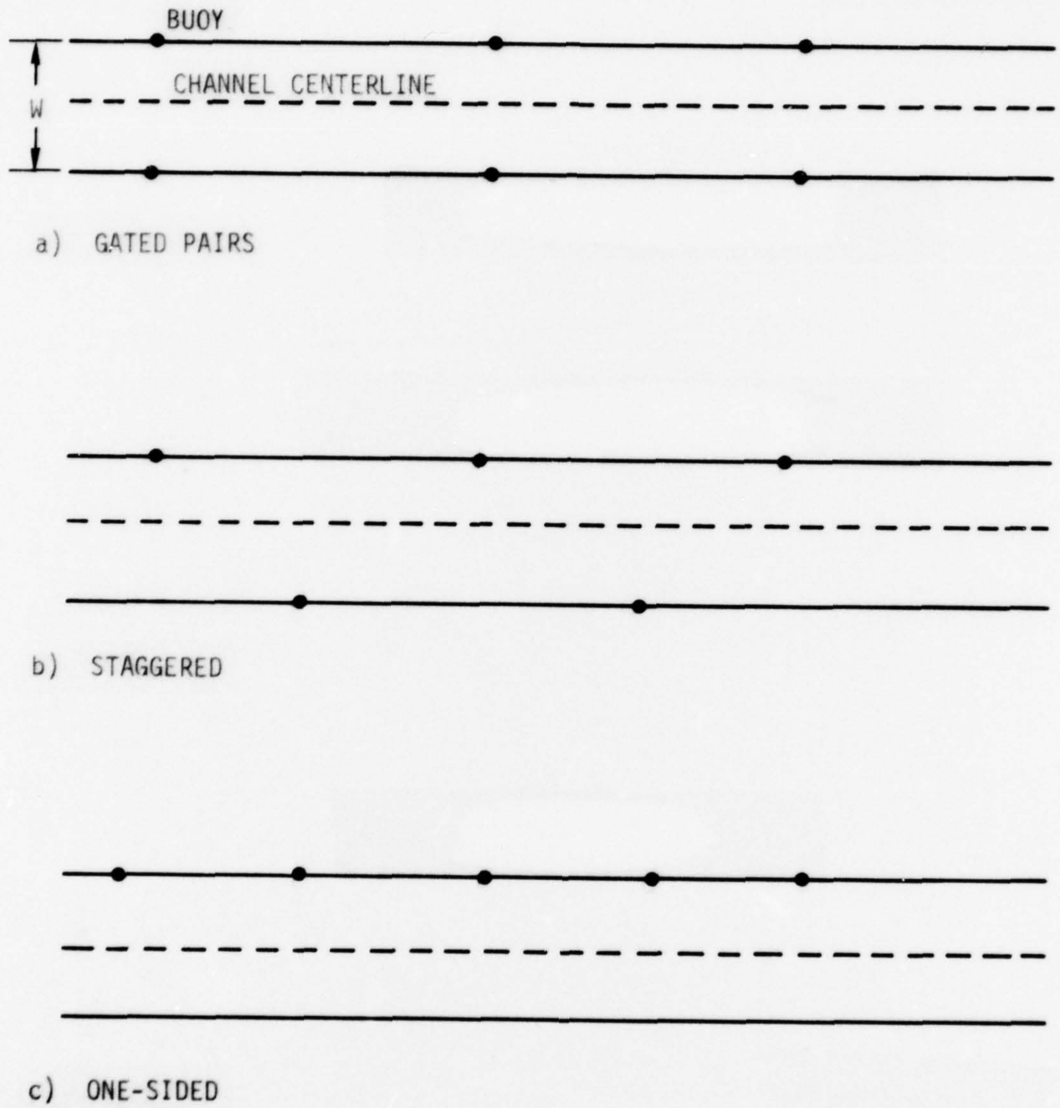


Figure F.14 Different Buoy Configurations for Marking a Straight Channel

F.3.4 Rudder and Throttle

The rudder and helm are modeled as is shown in Figure F.11. The rudder angle is limited by the physical stops of the helm. The rudder angle can be changed up to a fixed limit in rate of change. The steering gear shown in Figure F.11 is equivalent to a time lag in the range where the rate is not limited.

A change in vessel speed is caused by a command from the pilot to the engine room by use of the engine order telegraph/ throttle control. (Bow and stern thruster contols may also be present on the vessel.) The throttle control is modeled as a time delay followed by a time lag in throttle change. The engine RPM is a direct function of the throttle setting. The vessel speed is also modeled as function of RPM. The vessel speed transient response can be modeled as an exponential buildup or decay corresponding to a change in RPM. The effect of vessel speed changes were not studied as part of this effort.

F.3.5 Environmental Effects

The single environmental effect considered in the Phase I effort has been a steady cross current which is represented in the vessel equations of motion discussed previously. This cross current causes the vessel to have a constant crab angle to continue movement along a fixed channel line. The current is represented mathematically by a vector having magnitude and direction.

The current is typically represented by a vector which changes with position location within the harbor and time. This is especially important in modeling the process of navigation around land features which protrude into the channel such as along Sandy Hook channel.

Another effect that causes torque on the vessel is the presence of cross winds. This effect is a function of the

shape of the hull and the possible container loading on the vessel. This torque must be countered by a steady rudder deflection. As the wind changes the compensation must also change which will cause transient vessel yawing motion. The effects of winds will be considered in Phase II.

Another effect of the wind is the sea state that it will cause. Rough seas will cause yawing motion which will increase the inaccuracy of the pilot's state estimation capability. The same is true for the helmsman's ability to hold a steady course. The effect of heavy seas can be modeled as sinusoidal motions in heave, sway, roll, pitch, yaw of the vessel about its nominal position. The sinusoidal motions are usually of fixed frequencies with a randomness in magnitude and phase.

The pilot's visibility is affected by time of day, cloud cover, and amount of precipitation that may exist. Different effects are present from rain, snow, and fog. Associated with each of these features are the tranmissibility of light and the clearness of sounds (bells, gongs, fog horns). Also, these effects along with sea state affect the clutter in the vessel's radar returns.

F.3.6 Harbor Geometry

In the Phase I study the channel elements that were considered included bends, straight passages, harbor entrances, and anchorages. Other variations which can be considered include a merge point, a bifurcation, and a traffic circle. Bends may consist of sharp turns or a series of straight line segments, each with a small heading change. The bend also can be truncated as in Figure F.9.

Shoreline features can also affect the Process of Navigation. The shore line can represent a continuous boundary to a channel, or it can represent an occasional restriction or a source of an

obstacle (e.g., bridge pier). On the other hand, the shoreline features may have objects which can be directly used to aid navigation such as a smokestack or a street direction that is visible from sea. The change in the visual scene caused by the background shoreline provides rate information to the pilot as does the relative movement of the vessel with respect to visible aids to navigation.

The final important feature of the harbor geometry is the depth of the channels with respect to mean sea level. The actual depth of the channel at a particular time and place will be a function of the tide and wind effects.

F.3.7 Miscellaneous Elements

There are miscellaneous elements which affect the Process of Navigation that must eventually be considered when modeling that process. These include the following:

(1) Charts - their accurateness and completeness.

(2) Inter-vessel communications - this is a source of channel status information as well as a method of planning where two vessels can safely pass.

(3) Traffic and weather advisories - this service provided by the Coast Guard gives the pilot information which he uses to govern the manner in which he proceeds. If conditions are too adverse, the pilot can choose to wait for a more favorable time and state of the channel.

(4) Rules and regulations - these govern what is considered good seamanship. They impact pilot navigation objectives and intentions in applicable situations.

(5) Local custom - this determines the way a given channel is typically navigated in a given locality. This information comes from local training and can not be determined by examining a chart.

(6) The presence and motion of another vessel - this includes the vessel's dimensions and its maneuverability.

None of these miscellaneous features were included directly in the model used for the present study.

APPENDIX G
SAMPLE MODEL OUTPUT

This appendix contains a sample of each of the basic types of model output. The reader may refer to Section 3.3.4.2 of the main body of the report for clarification of the output content.

```
03/19/78  1M191111 VARGUS 0373AA190     000373          10    700                          DATE 031978       PAGE   34

GATED        CONFIGURATION:  TWO MILE SPACING

TIME =  450. ON SEGMENT  1 X =     8896. Y =     3088. XDOT =  19.638 YDOT =  -2.545
ERROR DATA      TRUE    BIAS  COMMON RANDOM OBSERVED
ORIENTATION    1.571    .000    .000    .000  1.571
HEADING        1.622   -.004    .000    .000  1.619
RUDDER          .087    .000    .000    .000   .087

BUOY        D          PSI          D'        PSI'
  5.     6111.8      -.103      6116.9      -.065
  9.    18106.5      -.069     18108.3      -.022
 13.    30105.5      -.062     30106.5      -.013
  6.     6123.3       .028      6116.9       .065
 10.    18110.4      -.024     18108.3       .022
 14.    30107.8      -.035     30106.5       .013

NO.  LOP TYPE        BUOYS              ALT OBS    OR CTD    OR ATP        LOP VAR
 1        3.      5.  0.  0.  0.          -.124     1.520     -.051      167852.7
 2        5.      5.  9.  6. 10.          -.018    -1.552    -3.123       14542.4
 3        5.      9. 13. 10. 14.          -.009    -1.563    -3.134       14455.4
 4        4.      5.  6.  0.  0.           .000    -1.557    -3.127    13660401.1
 5        1.      5.  0.  0.  0.       5733.439     3.090     1.520     1419520.6
 6        6.      5.  6.  0.  0.           .000     1.556     -.014       29846.3
 7        2.      5.  9.  0.  0.           .041     1.502     -.068       26257.0
 8        1.      6.  0.  0.  0.       5744.180     3.221     1.651     1424843.9
 9        2.      6. 10.  0.  0.           .059    -1.464    -3.035       63908.9
10        3.      6.  0.  0.  0.           .000     1.651      .080       15473.0
11        2.      9. 13.  0.  0.           .006     1.543     -.028       20247.4
12        2.     10. 14.  0.  0.           .015    -1.528    -3.098       63912.3

CTD:      TRUE=      -87.6 FIN EST=      -70.4 FIN ANT VAR=        431.
          DR:                                                 CTD EST=      -87.5 ANT VAR=        454. WEIGHT= .947
          PRIMARY:     INDICES=( 1, 3) X=      9906.2 Y=     2762.6 CTD EST=      237.4 ANT VAR=      13803. WEIGHT= .031
          SECONDARY:   INDICES=( 1, 2) X=      9906.2 Y=     2762.6 CTD EST=      237.4 ANT VAR=      20069. WEIGHT= .021

CTDDOT:   TRUE=       2.54 FIN EST=       2.57 FIN ANT VAR=        .16

ATP:      TRUE=     8896.2 FIN EST=     8840.7 FIN ANT VAR=      12506.
          DR:                                                 ATP EST=     8829.2 ANT VAR=      12835. WEIGHT= .974
          PRIMARY:     INDICES=( 5, 8) X=      9276.2 Y=     3068.5 ATP EST=     9276.2 ANT VAR=     747338. WEIGHT= .017
          SECONDARY:   INDICES=( 8, 9) X=      9278.0 Y=     3104.6 ATP EST=     9278.0 ANT VAR=    1410132. WEIGHT= .009

ATPDOT:   TRUE=      19.64 FIN EST=      19.64 FIN ANT VAR=       4.01

H:        TRUE=      1.622 FIN EST=      1.623 FIN EST VAR=     .00003
          DR:        H EST=      1.626 ANT VAR=     .00006 WEIGHT= .555
          PRIMARY:   H EST=      1.619 ANT VAR=     .00008 WEIGHT= .445

HDOT:     TRUE=    -.00014 FIN EST=    -.00012 FIN EST VAR=   .0000002
          DR:                                           HDOT EST=     .00029 ANT VAR=   .0000043 WEIGHT= .048
          PRIMARY:     DPSI=       .024 RPSID=        .000 HDOT EST=    -.00014 ANT VAR=   .0000004 WEIGHT= .477
          SECONDARY:   DPSI=       .028 RPSID=        .000 HDOT EST=    -.00014 ANT VAR=   .0000004 WEIGHT= .475

R:        TRUE=       .087 FIN EST=       .087 FIN EST VAR=     .00008

HD=    1.497 DELTD=      .087 DELTC=      .087 DTURN=       .000 DRTT=       .083
```

LOP TYPE KEY:
1. Distance to buoy
2. Angle between buoys
3. Angle relative to track
4. Distance difference
5. Difference between angles between bouys
6. Difference (sum) of angles relative to track

Figure G.1 Detailed Time Period Output

03/19/78 18191111 VARGUS 0373AAT90 000373 10 700 DATE 031978 PAGE 72

GATED CONFIGURATION: TWO MILE SPACING

TRIAL NO. 1 PAGE 1

TIME	CROSS TRACK DISTANCE TRUE	CROSS TRACK DISTANCE EST	CROSS TRACK DISTANCE ANT SD	CTD RATE TRUE	CTD RATE EST	CTD RATE ANT SD	ALONG TRACK POSITION TRUE	ALONG TRACK POSITION EST	ALONG TRACK POSITION ANT SD	ATP RATE TRUE	ATP RATE EST	ATP RATE ANT SD
0.	5.6	5.1	80.	.069	-.206	.45	1.0	234.1	341.	19.936	19.915	2.00
10.	6.3	25.8	57.	.064	-.238	.43	198.4	210.7	233.	19.936	19.912	2.00
20.	6.9	27.9	47.	.067	-.349	.43	397.7	482.4	184.	19.936	19.902	2.00
30.	7.6	4.0	40.	.069	-.405	.43	597.1	502.1	154.	19.936	19.897	2.00
40.	8.3	-.1	41.	.077	-.355	.44	796.4	653.1	132.	19.937	19.902	2.00
50.	9.2	-38.5	37.	.103	-.332	.44	995.8	715.2	116.	19.939	19.904	2.00
60.	10.4	-32.9	33.	.138	-.218	.44	1195.2	825.4	102.	19.941	19.914	2.00
70.	12.0	-19.1	31.	.176	-.161	.43	1394.6	1095.8	91.	19.944	19.919	2.00
80.	14.0	-7.0	29.	.217	-.079	.43	1594.1	1332.1	82.	19.946	19.925	2.00
90.	16.3	-7.8	28.	.260	-.011	.43	1793.6	1576.2	73.	19.949	19.931	2.00
100.	19.1	-2.4	27.	.300	.043	.42	1993.1	1778.8	65.	19.952	19.935	2.00
110.	22.3	6.9	25.	.334	.170	.42	2192.6	1952.8	58.	19.954	19.944	2.00
120.	25.8	13.5	22.	.363	.131	.41	2392.1	2230.1	51.	19.956	19.941	2.00
130.	29.5	13.7	18.	.377	.141	.41	2591.7	2500.2	47.	19.956	19.942	2.00
140.	33.3	20.7	14.	.383	.229	.41	2791.3	2719.9	47.	19.957	19.948	2.00
150.	37.2	176.9	11.	.394	.208	.41	2990.8	2932.0	49.	19.958	19.947	2.00
160.	41.2	177.8	12.	.396	.143	.41	3190.4	3131.4	53.	19.958	19.943	2.00
170.	45.4	179.0	12.	.447	.361	.37	3390.0	3330.9	57.	19.957	19.953	2.00
180.	49.9	182.6	13.	.438	.492	.34	3589.6	3530.4	60.	19.954	19.956	2.00
190.	53.9	190.9	13.	.344	.552	.32	3789.1	3730.0	63.	19.944	19.954	2.00
200.	56.3	194.0	13.	.120	.229	.33	3988.4	3929.5	66.	19.919	19.927	2.00
210.	56.1	197.5	14.	-.167	-.149	.35	4187.4	4127.3	69.	19.880	19.882	2.00
220.	52.9	195.1	14.	-.467	-.420	.37	4386.0	4327.8	72.	19.835	19.838	2.00
230.	46.7	187.7	15.	-.773	-.643	.38	4584.0	4526.2	75.	19.780	19.795	1.99
240.	37.4	178.2	15.	-1.083	-.947	.40	4781.6	4724.2	77.	19.722	19.740	1.99
250.	24.9	168.7	15.	-1.435	-1.526	.45	4978.4	4921.6	80.	19.647	19.634	1.98
260.	8.8	153.5	16.	-1.764	-2.030	.50	5174.5	5117.4	82.	19.571	19.525	1.98
270.	-10.2	120.6	16.	-2.024	-2.459	.54	5369.9	5315.1	84.	19.511	19.428	1.97
280.	-31.4	96.0	17.	-2.212	-2.692	.58	5564.8	5509.3	86.	19.472	19.374	1.96
290.	-54.1	57.3	18.	-2.322	-2.847	.61	5759.4	5700.4	88.	19.451	19.342	1.96
300.	-77.6	28.4	20.	-2.353	-2.942	.63	5953.9	5891.6	90.	19.450	19.325	1.96
310.	-100.9	-5.2	21.	-2.301	-3.055	.65	6148.5	6086.6	92.	19.466	19.304	1.96
320.	-123.3	-37.7	22.	-2.161	-2.982	.67	6343.3	6274.6	94.	19.495	19.323	1.96
330.	-143.8	-71.1	22.	-1.930	-2.827	.68	6538.4	6470.3	95.	19.533	19.355	1.96
340.	-161.3	-108.0	23.	-1.554	-2.246	.64	6734.0	6663.9	97.	19.580	19.460	1.97
350.	-174.9	-128.6	23.	-1.150	-1.785	.61	6930.0	6858.5	99.	19.618	19.522	1.98
360.	-184.3	-147.0	23.	-.742	-1.375	.58	7126.3	7049.6	100.	19.647	19.565	1.99
370.	-189.7	-165.0	23.	-.332	-.943	.56	7322.9	7238.0	102.	19.669	19.603	1.99
380.	-191.0	-155.5	22.	.079	-.688	.54	7519.7	7434.1	104.	19.684	19.614	2.00
390.	-188.1	-167.1	21.	.491	-.222	.53	7716.5	7632.9	105.	19.691	19.643	2.00
400.	-181.1	-162.4	21.	.903	.201	.52	7913.5	7829.4	107.	19.691	19.658	2.00
410.	-169.8	-162.2	21.	1.367	.959	.48	8110.3	8025.9	109.	19.674	19.667	2.00
420.	-154.0	-153.5	21.	1.774	1.470	.45	8306.9	8222.6	110.	19.655	19.657	2.01
430.	-134.6	-138.6	21.	2.105	1.877	.43	8503.4	8434.7	111.	19.642	19.648	2.00
440.	-112.2	-110.8	21.	2.363	2.327	.41	8699.8	8632.9	112.	19.636	19.637	2.00
450.	-87.6	-70.4	21.	2.545	2.572	.40	8896.2	8840.7	112.	19.638	19.636	2.00
460.	-61.5	-44.3	20.	2.651	2.751	.38	9092.6	9042.6	112.	19.647	19.641	2.00
470.	-34.8	-24.6	20.	2.678	2.901	.36	9289.1	9239.0	114.	19.661	19.646	2.00
480.	-8.2	2.2	20.	2.621	3.031	.35	9485.8	9435.5	116.	19.679	19.651	2.00
490.	17.3	33.6	19.	2.478	2.909	.33	9682.7	9644.1	115.	19.696	19.669	2.00
500.	40.9	57.1	19.	2.206	2.501	.31	9879.7	9840.8	117.	19.708	19.695	2.00

Figure G.2 Detailed Transit Output (Part 1 Cross Track Data and Along Track Data)

03/19/78 18191111 VARGUS 0373AAT90 000373 10 700 DATE 031978 PAGE 75

GATED CONFIGURATION: TWO MILE SPACING

TRIAL NO. 1 PAGE 2

TIME	HEADING TRUE	HEADING EST	HEADING ANT SD	HEADING RATE TRUE	HEADING RATE EST	HEADING RATE ANT SD	RUDDER	DESIRED HEADING	PILOT RUD CMD	HELM RUD CMD	HEADING ERROR	X	Y
0.	85.4	85.2	.500	.000	.000	.0279	.00	85.75	.00	-.57	-.59	-1.0	2994.4
10.	85.4	85.1	.376	.003	.003	.0276	-.49	85.75	.00	.00	-.60	198.4	2993.7
20.	85.5	84.9	.341	.004	.004	.0277	-.07	85.75	.00	-.76	-.90	397.7	2993.1
30.	85.5	84.8	.330	.007	.007	.0281	-.67	85.75	.00	-.72	-.96	597.1	2992.4
40.	85.6	85.1	.327	.012	.011	.0286	-.71	85.75	.00	.00	-.88	796.4	2991.7
50.	85.7	85.2	.328	.012	.012	.0287	-.10	85.75	.00	.00	-.60	995.8	2990.8
60.	85.8	85.5	.328	.012	.012	.0286	-.01	85.75	.00	.00	-.27	1195.2	2989.6
70.	86.0	85.6	.328	.012	.012	.0286	-.00	85.75	.00	.24	-.11	1394.6	2988.0
80.	86.1	85.9	.328	.011	.011	.0284	.21	85.75	.00	.42	.10	1594.1	2986.0
90.	86.2	86.0	.328	.009	.009	.0281	.39	85.75	.00	.49	.24	1793.6	2983.7
100.	86.3	86.1	.327	.007	.007	.0278	.48	85.75	.00	.50	.32	1993.1	2980.9
110.	86.3	86.4	.326	.004	.004	.0275	.50	85.75	.00	.71	.61	2192.6	2977.7
120.	86.3	86.2	.324	.001	.001	.0270	.68	85.75	.00	.00	.40	2392.1	2974.2
130.	86.3	86.2	.322	.001	.001	.0270	.09	85.75	.00	.00	.42	2591.7	2970.5
140.	86.4	86.4	.322	.001	.001	.0271	.01	85.75	.00	.69	.69	2791.3	2966.7
150.	86.4	86.3	.322	-.002	-.002	.0267	.60	85.75	.00	.00	.54	2990.8	2962.8
160.	86.3	86.1	.321	-.003	-.003	.0266	.08	85.75	5.00	5.00	.33	3190.4	2958.8
170.	86.1	85.7	.320	-.037	-.036	.0222	4.81	85.75	5.00	5.00	-.05	3390.0	2954.6
180.	85.6	85.2	.307	-.067	-.067	.0185	4.97	85.75	5.00	5.00	-.59	3589.6	2950.1
190.	84.8	84.5	.291	-.095	-.094	.0151	5.00	85.75	.00	.00	-1.25	3789.1	2946.1
200.	83.8	83.5	.274	-.096	-.096	.0152	.68	85.75	.00	.00	-2.24	3988.4	2943.7
210.	82.9	82.5	.266	-.092	-.093	.0160	.09	85.75	.00	.00	-3.21	4187.4	2943.9
220.	82.0	81.8	.263	-.092	-.092	.0163	.01	85.75	.00	.00	-3.99	4386.0	2947.1
230.	81.0	81.1	.263	-.093	-.093	.0164	.00	85.75	.00	.00	-4.67	4584.0	2953.3
240.	80.1	80.2	.264	-.094	-.094	.0165	.00	85.75	-5.00	-5.00	-5.59	4781.6	2962.6
250.	79.2	79.1	.264	-.071	-.072	.0198	-4.32	85.75	-5.00	-5.00	-6.61	4978.4	2975.1
260.	78.7	78.5	.276	-.043	-.044	.0236	-4.91	85.75	-5.00	-5.00	-7.27	5174.5	2991.2
270.	78.4	78.0	.294	-.018	-.019	.0269	-4.99	85.75	-5.00	-5.00	-7.79	5369.9	3010.2
280.	78.3	78.0	.311	.006	.005	.0249	-5.00	85.75	-5.00	-5.00	-7.76	5564.8	3031.4
290.	78.5	78.3	.327	.031	.029	.0329	-5.00	85.75	-5.00	-5.00	-7.49	5759.4	3054.1
300.	78.9	78.7	.340	.057	.054	.0359	-5.00	85.75	-5.00	-5.00	-7.01	5953.9	3077.6
310.	79.6	79.2	.351	.083	.080	.0388	-5.00	85.75	-5.00	-5.00	-6.57	6148.5	3100.9
320.	80.6	80.2	.361	.109	.106	.0415	-5.00	85.75	-5.00	-5.00	-5.59	6343.3	3123.3
330.	81.8	81.4	.370	.134	.131	.0441	-5.00	85.75	.00	.00	-4.38	6538.4	3143.8
340.	83.1	82.9	.377	.124	.125	.0427	-.19	85.75	.00	.00	-2.84	6734.0	3161.3
350.	84.3	84.1	.376	.121	.121	.0420	-.03	85.75	.00	.00	-1.62	6930.0	3174.9
360.	85.5	85.3	.374	.120	.120	.0416	-.00	85.75	.00	.00	-.46	7126.3	3184.3
370.	86.7	86.5	.373	.120	.120	.0413	-.00	85.75	.00	.00	.79	7322.9	3189.7
380.	87.4	87.3	.372	.120	.120	.0410	-.00	85.75	.00	.00	1.54	7519.7	3191.0
390.	89.1	88.7	.371	.120	.120	.0409	-.00	85.75	.00	.00	2.90	7716.5	3188.1
400.	90.4	89.9	.370	.121	.121	.0410	-.00	85.75	5.00	5.00	4.14	7913.5	3181.1
410.	91.4	91.2	.371	.088	.091	.0371	4.81	85.75	5.00	5.00	5.45	8110.3	3169.8
420.	92.1	91.9	.362	.062	.064	.0341	4.97	85.75	5.00	5.00	6.13	8306.9	3154.0
430.	92.6	92.4	.352	.038	.040	.0314	5.00	85.75	5.00	5.00	6.60	8503.4	3134.6
440.	92.9	93.0	.343	.015	.017	.0287	5.00	85.75	5.00	5.00	7.22	8699.8	3112.2
450.	92.9	93.0	.333	-.008	-.007	.0257	5.00	85.75	5.00	5.00	7.22	8896.2	3087.6
460.	92.7	92.8	.322	-.032	-.032	.0226	5.00	85.75	5.00	5.00	7.00	9092.6	3061.5
470.	92.3	92.4	.309	-.058	-.057	.0193	5.00	85.75	5.00	5.00	6.67	9289.1	3034.8
480.	91.6	92.0	.295	-.083	-.083	.0158	5.00	85.75	5.00	5.00	6.27	9485.8	3008.2
490.	90.6	90.9	.278	-.109	-.109	.0123	5.00	85.75	.00	.00	5.14	9682.7	2982.7
500.	89.5	89.7	.259	-.110	-.110	.0122	.68	85.75	.00	.00	3.92	9879.7	2959.1

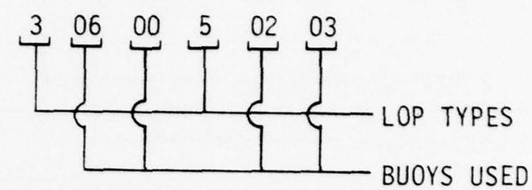
Figure G.3 Detailed Transit Output (Part 2.Heading, Pilot and Helmsman Data)

03/19/78 18141111 VARGUS 0373AAT90 000375 10 700 DATE 031978 PAGE 78

GATED CONFIGURATION: TWO MILE SPACING

	CTD			ATP		
TIME	TRUE	PRIMARY	SECONDARY	TRUE	PRIMARY	SECONDARY
0.	5.6	3060050203	3060050102	1.0	1010010600	1010020102
10.	6.3	3060050203	3060050102	198.4	1010010600	1010020102
20.	6.9	3060050203	3060050102	397.7	1010010600	1010020102
30.	7.6	3060050203	3060050102	597.1	1010010600	1060020607
40.	8.3	3060050203	3060050102	796.4	1010010600	1060020607
50.	9.2	3060050203	3060050102	995.8	1010010600	1060020607
60.	10.4	3060050203	3060050102	1195.2	1010010600	1060020607
70.	12.0	3060050203	3060050102	1394.6	1010010600	1060020607
80.	14.0	3060050203	3060050102	1594.1	1010010600	1060020607
90.	16.3	3060050203	3060050102	1793.6	1010010600	1060020607
100.	19.1	3060050203	3060040106	1993.1	1010010600	1060020607
110.	22.3	3060040106	3060050203	2192.6	1010010600	1060020607
120.	25.8	3060040106	3060050203	2392.1	1010010600	1060020607
130.	29.5	3060040106	3060050203	2591.7	1010010600	1060020607
140.	33.3	3060040106	3060050203	2791.3	1010010600	1060020607
150.	37.2	3060040106	1060020607	2990.8	1060020607	3010030600
160.	41.2	3060050203	3060050102	3190.4	1010010600	1010020102
170.	45.4	3060050203	3060050102	3390.0	1010010600	1010020102
180.	49.9	3060050203	3060050102	3589.6	1010010600	1010020102
190.	53.9	3060050203	3060050102	3789.1	1010010600	1010020102
200.	56.3	3060050203	1060020607	3988.4	1010010600	1010020102
210.	56.1	3060050203	1060020607	4187.4	1010010600	1010020102
220.	52.9	3060050203	1060020607	4386.0	1010010600	1010020102
230.	46.7	3060050203	1060020607	4584.0	1010010600	1010020102
240.	37.4	3060050203	3060050102	4781.6	1010010600	1010020102
250.	24.9	3060050203	3060050102	4978.4	1010010600	1010020102
260.	8.8	3060050203	3060050102	5174.5	1010010600	1010020102
270.	-10.2	3010050203	3010050102	5369.9	1010010600	1060020607
280.	-31.4	3010050203	3010050102	5564.8	1010010600	1060020607
290.	-54.1	3010050203	3010050102	5759.4	1010010600	1060020607
300.	-77.6	3010050203	1010020102	5953.9	1010010600	1060020607
310.	-100.9	1010020102	3010050203	6148.5	1010010600	1060020607
320.	-123.3	1010020102	3010050203	6343.3	1010010600	1060020607
330.	-143.8	1010020102	3010050203	6538.4	1010010600	1060020607
340.	-161.3	1010020102	3010050203	6734.0	1010010600	1060020607
350.	-174.9	1010020102	3010050203	6930.0	1010010600	1060020607
360.	-184.3	1010020102	3010050203	7126.3	1010010600	1060020607
370.	-189.7	3010050203	3010050102	7322.9	1010010600	1060020607
380.	-191.0	3010050102	1010030100	7519.7	1010010600	1060020607
390.	-188.1	3010050102	3010050203	7716.5	1010010600	1060020607
400.	-181.1	3010050203	3010050102	7913.5	1010010600	1060020607
410.	-169.8	3010050203	1010020102	8110.3	1010010600	1060020607
420.	-154.0	3010050203	1010020102	8306.9	1010010600	1060020607
430.	-134.6	3010050203	1010020102	8503.4	1010010600	1060020607
440.	-112.2	3010050203	3010050102	8699.8	1010010600	1060020607
450.	-87.6	3010050203	3010050102	8896.2	1010010600	1060020607
460.	-61.5	3010050203	3010050102	9092.6	1010010600	1060020607
470.	-34.8	3010050203	3010050102	9289.1	1010010600	1060020607
480.	-8.2	3010050102	3010050203	9485.8	1010010600	1060020607
490.	17.3	3060050102	3060050203	9682.7	1010010600	1010020102
500.	40.9	3060050102	3060050203	9879.7	1010010600	1010020102

OUTPUT FORMAT:



Buoy indices 1, 2, ... 5 are left-side buoys.
Buoy indices 6, 7, ...10 are right-side buoys.
For the specific example shown, a Type 5 LOP is a difference between angles between buoys. In this case, only the left side buoys are listed. The corresponding right-side buoys would be 7 and 8 (i.e. the 2nd and 3rd gates ahead are being used).

Figure G.4 Detailed Transit Output (Part 3.LOP Pairs Used)

```
03/19/78  15:41111 VARGUS 0373AA190    000373        10    700                                          DATE 031978        PAGE    82
STATISTICS FOR TRIAL NO.  1
     --CROSS TRACK DISTANCE WEIGHTS--  --ALONG TRACK POSITION WEIGHTS--  ---------HEADING WEIGHTS--------
        DR       PRIMARY   SECONDARY        DR         PRIMARY   SECONDARY       DR        PRIMARY   SECONDARY
       .917        .051       .032              .925        .048        .027         .057        .481        .463
            MEAN        MEAN                         MEAN                          MEAN        MEAN
          EST-TRUE  ABS(EST-TRUE)    ACT SD        ANT SD                        EST-TRUE  ABS(EST-TRUE)    ACT SD        MEAN
CTD           20.5         38.7        52.7          20.2  CTD RATE              -.264         .317        .282       ANT SD
ATP         -147.5        153.0       103.4          95.3  ATP RATE              -.035         .037        .043         .446
HEADING       -.23          .27         .22           .32  HDG RATE              -.000         .001        .001        1.994
AVERAGE RUDDER =   -.0238 AVERAGE ABS(RUDDER) =   1.8003 ACTUAL RUDDER STANDARD DEVIATION =    2.8658              .027
NO. OF TIMES PILOT COMMAND CHANGED =   16.
PER CENT OF TIME SHIP WAS UNDER PILOT CONTROL = 33.88
```

Figure G.5 Transit Summary Data

03/19/78 TRI#1111 VARGUS 037344190 000373 10 700 DATE 031978 PAGE 189

GATED CONFIGURATION: TWO MILE SPACING

AVERAGE AFTER 10 TRIALS PAGE 1

	AVG CTD	CTD SD	E(CTD**3)	E(CTD**4)	AVG HDG	HDG SD	E(HDG**3)	E(HDG**4)	AVG X	AVG Y
0.	.517960+00	.131623+02	-.177511+04	.965015+05	.855754+02	.103459+01	.626955+06	.536754+08	-.100000+01	.299968+04
10.	.180052+01	.131460+02	-.609120+03	.718806+05	.855467+02	.994430+00	.626305+06	.536000+08	.198371+03	.299819+04
20.	.315727+01	.141676+02	.866119+03	.860263+05	.854572+02	.893123+00	.624294+06	.533679+08	.397736+03	.299684+04
30.	.441479+01	.159218+02	.277945+04	.158527+06	.853271+02	.834842+00	.621421+06	.530393+08	.597092+03	.299559+04
40.	.537009+01	.179224+02	.472660+04	.284965+06	.851996+02	.858167+00	.618651+06	.527248+08	.796419+03	.299463+04
50.	.595484+01	.199402+02	.616284+04	.444595+06	.850728+02	.958011+00	.615939+06	.524195+08	.995697+03	.299405+04
60.	.614729+01	.216955+02	.691098+04	.600917+06	.849390+02	.118408+01	.613160+06	.521112+08	.119492+04	.299365+04
70.	.590113+01	.230024+02	.715415+04	.707366+06	.848103+02	.147433+01	.610574+06	.518292+08	.139408+04	.299410+04
80.	.515472+01	.240199+02	.705331+04	.761468+06	.847197+02	.174976+01	.608843+06	.516459+08	.159319+04	.299485+04
90.	.393596+01	.252206+02	.660719+04	.846914+06	.846836+02	.196579+01	.606268+06	.515922+08	.179210+04	.299606+04
100.	.239530+01	.271149+02	.455278+04	.113646+07	.846816+02	.215020+01	.606420+06	.516203+08	.199098+04	.299760+04
110.	.736849+00	.299929+02	-.203288+04	.192242+07	.846642+02	.228900+01	.606202+06	.516048+08	.218980+04	.299926+04
120.	-.943292+00	.339444+02	-.171212+05	.365367+07	.846057+02	.234876+01	.607015+06	.514746+08	.238857+04	.300094+04
130.	-.275738+01	.388797+02	-.443396+05	.684725+07	.845432+02	.234522+01	.605666+06	.513217+08	.258729+04	.300276+04
140.	-.479472+01	.444780+02	-.851059+05	.118485+08	.845092+02	.227518+01	.604853+06	.512248+08	.278596+04	.300479+04
150.	-.698979+01	.504000+02	-.138870+06	.188344+08	.844786+02	.215050+01	.604056+06	.511266+08	.298459+04	.300699+04
160.	-.933143+01	.564043+02	-.206358+06	.283509+08	.844576+02	.199300+01	.603440+06	.510478+08	.318321+04	.300933+04
170.	-.117958+02	.622670+02	-.288740+06	.413079+08	.844469+02	.181729+01	.603044+06	.509941+08	.338180+04	.301180+04
180.	-.143205+02	.677932+02	-.386143+06	.586587+08	.844290+02	.162182+01	.602493+06	.509231+08	.358039+04	.301432+04
190.	-.169096+02	.726334+02	-.495399+06	.806081+08	.844095+02	.153151+01	.602008+06	.508652+08	.377895+04	.301691+04
200.	-.196170+02	.763739+02	-.608374+06	.105761+09	.844206+02	.170393+01	.602389+06	.509167+08	.397748+04	.301962+04
210.	-.224624+02	.785880+02	-.710754+06	.130523+09	.845035+02	.211032+01	.604559+06	.511840+08	.417595+04	.302246+04
220.	-.252364+02	.784991+02	-.780524+06	.148880+09	.846179+02	.265616+01	.607679+06	.515742+08	.437432+04	.302524+04
230.	-.277323+02	.775039+02	-.799853+06	.155173+09	.847206+02	.325027+01	.610785+06	.519764+08	.457258+04	.302773+04
240.	-.298549+02	.742323+02	-.760322+06	.147447+09	.847892+02	.381343+01	.613277+06	.523161+08	.477069+04	.302985+04
250.	-.316555+02	.696855+02	-.674222+06	.128060+09	.848267+02	.426974+01	.615024+06	.525607+08	.496861+04	.303164+04
260.	-.331959+02	.648646+02	-.565736+06	.103373+09	.848659+02	.454431+01	.616485+06	.527666+08	.516634+04	.303319+04
270.	-.345945+02	.612575+02	-.464819+06	.797211+08	.849210+02	.464074+01	.617900+06	.529391+08	.536392+04	.303459+04
280.	-.358364+02	.604195+02	-.401390+06	.628216+08	.849924+02	.456501+01	.619266+06	.530834+08	.556141+04	.303584+04
290.	-.368526+02	.631810+02	-.398180+06	.576089+08	.850560+02	.434746+01	.620151+06	.531555+08	.575888+04	.303685+04
300.	-.376502+02	.691948+02	-.468922+06	.687533+08	.851187+02	.400560+01	.620786+06	.531865+08	.595640+04	.303765+04
310.	-.382543+02	.774843+02	-.620314+06	.101033+09	.851939+02	.354202+01	.621532+06	.532215+08	.615400+04	.303825+04
320.	-.386965+02	.868580+02	-.847217+06	.157653+09	.853098+02	.300221+01	.623166+06	.533577+08	.635171+04	.303870+04
330.	-.389356+02	.962049+02	-.113072+07	.237770+09	.854855+02	.242385+01	.626215+06	.536613+08	.654953+04	.303894+04
340.	-.387943+02	.104691+03	-.143510+07	.333725+09	.856975+02	.187298+01	.630272+06	.540911+08	.674746+04	.303879+04
350.	-.380699+02	.111673+03	-.170757+07	.429238+09	.859081+02	.149768+01	.634602+06	.545663+08	.694550+04	.303807+04
360.	-.366400+02	.116820+03	-.189831+07	.505528+09	.860898+02	.144487+01	.638592+06	.550235+08	.714360+04	.303664+04
370.	-.344939+02	.120006+03	-.197815+07	.548991+09	.862323+02	.174352+01	.642010+06	.554299+08	.734174+04	.303449+04
380.	-.317449+02	.121066+03	-.193717+07	.551722+09	.863612+02	.227521+01	.645441+06	.558560+08	.753987+04	.303174+04
390.	-.285315+02	.119874+03	-.178221+07	.513095+09	.865204+02	.291269+01	.649866+06	.564153+08	.773796+04	.302853+04
400.	-.247773+02	.116395+03	-.152611+07	.438994+09	.866706+02	.354884+01	.654313+06	.569403+08	.793594+04	.302478+04
410.	-.203435+02	.110695+03	-.119635+07	.343037+09	.867314+02	.408914+01	.656755+06	.573344+08	.813378+04	.302034+04
420.	-.153441+02	.103098+03	-.843043+06	.244852+09	.866900+02	.454042+01	.656829+06	.574004+08	.833146+04	.301534+04
430.	-.101372+02	.940598+02	-.517789+06	.160421+09	.866158+02	.491680+01	.656074+06	.573652+08	.852898+04	.301014+04
440.	-.493507+01	.841857+02	-.255261+06	.977837+08	.865222+02	.514567+01	.654695+06	.572466+08	.872635+04	.300493+04
450.	.148889+00	.743524+02	-.713964+05	.575845+08	.863996+02	.536885+01	.652412+06	.570091+08	.892359+04	.299985+04
460.	.499489+01	.658765+02	.359016+05	.354708+08	.862512+02	.542295+01	.649236+06	.566501+08	.912071+04	.299501+04
470.	.950670+01	.605507+02	.821506+05	.252882+08	.860718+02	.533283+01	.644979+06	.561436+08	.931777+04	.299049+04
480.	.135981+02	.601049+02	.919376+05	.228649+08	.858567+02	.506934+01	.639466+06	.554696+08	.951479+04	.298641+04
490.	.171156+02	.648553+02	.927848+05	.285829+08	.856115+02	.463232+01	.632971+06	.546564+08	.971181+04	.298288+04
500.	.199465+02	.733832+02	.109181+06	.471263+08	.853527+02	.407410+01	.626036+06	.537933+08	.990886+04	.298005+04

Figure G.6 Detailed Monte Carlo Statistics Data (Part 1.Cross Track and Heading.State Information Data for Other States is Identical)

05/19/78 IRI41III VARGUS 0373AAT90 000373 10 700 DATE 031978 PAGE 192

GATED CONFIGURATION: TWO MILE SPACING

AVERAGE AFTER 10 TRIALS PAGE 2

	CROSS TRACK DISTANCE				CROSS TRACK DISTANCE RATE			
	EST-TRUE	ABS(EST-TRUE)	ACTUAL SD	ANT SD	EST-TRUE	ABS(EST-TRUE)	ACTUAL SD	ANT SD
0.	.292588180+02	.586467652+02	.118995732+03	.655604933+13	-.142766444+00	.278993543+00	.303460237+00	.449592806+00
10.	.426457720+02	.854236050+02	.124950621+03	.630075520+02	-.018876750-01	.277603093+00	.356025651+00	.423952628+00
20.	.585894208+02	.894515181+02	.120217840+03	.512935152+02	-.292553124-01	.323506437+00	.347849333+00	.418120998+00
30.	.629984713+02	.894231644+02	.116365435+03	.427559695+02	-.532304649-01	.304279344+00	.383681785+00	.413479496+00
40.	.811338358+02	.915770769+02	.117351564+03	.381448078+02	-.044726846-01	.283083215+00	.342268429+00	.414473671+00
50.	.790966358+02	.957173014+02	.123379354+03	.345582395+02	-.649618702-01	.294748154+00	.353834521+00	.410547436+00
60.	.780402470+02	.919507504+02	.122065982+03	.322450151+02	-.356080006-01	.283066746+00	.360879638+00	.416850314+00
70.	.792209253+02	.938295565+02	.125260088+03	.301453373+02	-.638381504-01	.269297477+00	.334433299+00	.421713151+00
80.	.748831766+02	.881630797+02	.118979873+03	.284962080+02	-.991020650-01	.254898377+00	.333964575+00	.430294786+00
90.	.743048582+02	.848864307+02	.113529296+03	.271859400+02	-.143052118+00	.286343984+00	.342434589+00	.438596305+00
100.	.633770342+02	.745054693+02	.100635191+03	.260573819+02	-.112981450+00	.277469676+00	.324422844+00	.441480346+00
110.	.501530264+02	.621217136+02	.838850079+02	.244867318+02	-.031640190-01	.240148814+00	.278856467+00	.437036064+00
120.	.402516813+02	.488230562+02	.678752975+02	.220668416+02	-.292539385-01	.272272103+00	.313750349+00	.435026217+00
130.	.242444212+02	.311640654+02	.442468686+02	.185230660+02	-.751513867-01	.298471660+00	.350977998+00	.440742351+00
140.	.152874123+02	.198254206+02	.277066853+02	.150213870+02	-.567970071-01	.266941689+00	.329368230+00	.442751784+00
150.	.365948687+02	.695592594+02	.990956621+02	.123068253+02	-.801667203-01	.314055871+00	.348898493+00	.443233319+00
160.	.357516484+02	.683124046+02	.906123495+02	.135673934+02	-.927293766-01	.310977895+00	.335595936+00	.445963141+00
170.	.316870905+02	.693613634+02	.963225842+02	.143064555+02	-.819057934-01	.271685566+00	.299543254+00	.444190826+00
180.	.317812231+02	.694109058+02	.945714149+02	.148981169+02	-.957522634-01	.292003050+00	.331622552+00	.443984047+00
190.	.323862371+02	.704017567+02	.942733326+02	.156950547+02	-.944430698-01	.313044228+00	.349144568+00	.444387939+00
200.	.310162206+02	.712257566+02	.942878056+02	.163213911+02	-.163209479+00	.333476748+00	.358609807+00	.452602621+00
210.	.245206333+02	.705534477+02	.938486776+02	.167405558+02	-.177799629+00	.312904261+00	.394306500+00	.458023492+00
220.	.299281023+02	.708619328+02	.918343306+02	.172039289+02	-.138898332+00	.342285585+00	.412111916+00	.458630785+00
230.	.309888775+02	.668181953+02	.881426229+02	.176733136+02	-.101898516+00	.264220409+00	.332472399+00	.455436803+00
240.	.296402578+02	.673562145+02	.890619507+02	.180874677+02	-.614303765-01	.236380585+00	.309840068+00	.452462662+00
250.	.289003435+02	.677372952+02	.870861618+02	.183704014+02	-.378578175-01	.214304380+00	.271941166+00	.454607665+00
260.	.291164937+02	.637679133+02	.853820162+02	.189322269+02	-.785092749-01	.271669343+00	.330243383+00	.459754873+00
270.	.286742688+02	.615257716+02	.811236048+02	.192885141+02	-.133559244+00	.338282518+00	.401369840+00	.466706362+00
280.	.270590467+02	.615621295+02	.795480032+02	.196378288+02	-.117471472+00	.370120957+00	.440558247+00	.468638994+00
290.	.203944812+02	.570278063+02	.738495893+02	.199750671+02	-.112030582+00	.383695487+00	.456826858+00	.466406666+00
300.	.164361026+02	.533881578+02	.696892471+02	.203747866+02	-.116330096+00	.404194698+00	.478207953+00	.465029016+00
310.	.166594510+02	.502496510+02	.624215117+02	.204868150+02	-.150547897+00	.448604066+00	.526038248+00	.464232836+00
320.	.153607101+02	.479307451+02	.577424426+02	.204500771+02	-.190674497+00	.435074691+00	.510666519+00	.464501437+00
330.	.124491085+02	.455318380+02	.552481022+02	.205108974+02	-.212262733+00	.444376964+00	.526801795+00	.464472461+00
340.	.800944507+01	.427288154+02	.521001106+02	.205849910+02	-.161696952+00	.398165759+00	.482608020+00	.459264293+00
350.	.793461054+01	.394575138+02	.473468720+02	.204338040+02	-.144785309+00	.359487623+00	.440583747+00	.450931255+00
360.	.339120775+01	.395833216+02	.455034165+02	.202325273+02	-.908392705-01	.316336967+00	.419102781+00	.441002566+00
370.	-.157066402+01	.375047374+02	.466171761+02	.201109662+02	-.555735757-01	.327998497+00	.414850283+00	.433610763+00
380.	-.427924740+01	.377646494+02	.488319397+02	.200504117+02	-.125902500+00	.356121935+00	.435835287+00	.433731295+00
390.	-.679974586+01	.334155521+02	.454730968+02	.200237021+02	-.146367485+00	.367742155+00	.431959454+00	.437477425+00
400.	-.962137616+01	.338112631+02	.478185387+02	.199972239+02	-.130797818+00	.390718006+00	.428505525+00	.434309956+00
410.	-.100665363+02	.349732876+02	.498563261+02	.201215348+02	-.413613585-01	.340581495+00	.393893592+00	.423312057+00
420.	-.977517712+01	.371616020+02	.505478349+02	.203042979+02	-.217873526-01	.311613526+00	.359117448+00	.420958437+00
430.	-.945738018+01	.388903666+02	.500025043+02	.202881484+02	-.163345656-01	.307066526+00	.348453026+00	.424911145+00
440.	-.943818212+01	.413012704+02	.513815888+02	.202157881+02	.980179000-03	.268330805+00	.332584154+00	.428357709+00
450.	-.635403800+01	.437522554+02	.552318935+02	.202731934+02	-.288876292-02	.268732163+00	.337614212+00	.430765010+00
460.	-.657811224+01	.466050940+02	.580158763+02	.204586046+02	.109195425-01	.289622322+00	.366694744+00	.433983508+00
470.	-.572344553+01	.442593944+02	.572543159+02	.203887756+02	.275954066-01	.337183993+00	.374660578+00	.436476109+00
480.	-.126316980+01	.503234377+02	.640649071+02	.203943100+02	.302517351-01	.325951718+00	.360868707+00	.437798269+00
490.	-.103953570+01	.517178521+02	.639535193+02	.204242291+02	.423149923-01	.348773312+00	.394161578+00	.438293811+00
500.	-.394095844+01	.547546555+02	.653595800+02	.205217333+02	.138573832-01	.333651662+00	.363998085+00	.434639830+00

Figure G.7 Detailed Monte Carlo Statistics Data (Part 2.Cross Track Estimation Information)

03/19/78 19191111 VARGUS 0173AAT90 000373 10 700 DATE 031978 PAGE 201

GATED CONFIGURATION: TWO MILE SPACING

AVERAGE AFTER 10 TRIALS PAGE 5

	--CROSS TRACK DISTANCE	WEIGHTS--		--ALONG TRACK	POSITION WEIGHTS--		---------HEADING	WEIGHTS---------	
	DR	PRIMARY	SECONDARY	DR	PRIMARY	SECONDARY	DR	PRIMARY	SECONDARY
0.	.200	.415	.385	.100	.592	.308	.000	.505	.495
10.	.451	.281	.267	.626	.245	.129	.050	.479	.470
20.	.668	.169	.163	.556	.291	.153	.046	.480	.471
30.	.709	.146	.144	.705	.194	.101	.048	.480	.472
40.	.797	.102	.101	.681	.208	.112	.049	.480	.472
50.	.814	.094	.092	.754	.160	.087	.049	.480	.471
60.	.859	.072	.069	.734	.172	.094	.049	.480	.471
70.	.861	.071	.068	.747	.162	.091	.050	.480	.470
80.	.877	.063	.060	.749	.159	.092	.052	.478	.470
90.	.890	.057	.053	.744	.161	.095	.054	.477	.469
100.	.895	.054	.051	.732	.167	.102	.055	.477	.468
110.	.859	.095	.046	.716	.175	.109	.053	.478	.469
120.	.787	.176	.037	.706	.185	.109	.052	.479	.470
130.	.678	.296	.026	.727	.184	.089	.054	.478	.469
140.	.628	.358	.014	.820	.124	.056	.054	.478	.469
150.	.613	.356	.031	.939	.033	.028	.054	.478	.468
160.	.981	.010	.009	.999	.001	.000	.055	.477	.467
170.	.980	.013	.007	.999	.000	.000	.055	.478	.467
180.	.988	.007	.005	1.000	.000	.000	.056	.478	.466
190.	.978	.011	.010	.999	.001	.000	.057	.478	.465
200.	.970	.021	.009	1.000	.000	.000	.061	.476	.463
210.	.971	.018	.011	.998	.001	.001	.063	.474	.463
220.	.980	.013	.007	.999	.001	.000	.063	.474	.462
230.	.968	.020	.012	.999	.001	.000	.061	.475	.464
240.	.966	.016	.018	.999	.001	.000	.058	.476	.465
250.	.971	.015	.014	.999	.001	.000	.057	.477	.466
260.	.964	.014	.022	.998	.001	.001	.057	.476	.467
270.	.963	.017	.020	.998	.002	.001	.059	.475	.466
280.	.965	.016	.019	.996	.003	.001	.059	.475	.466
290.	.959	.024	.016	.997	.002	.001	.059	.476	.466
300.	.954	.024	.022	.998	.001	.001	.059	.475	.466
310.	.958	.023	.019	.998	.002	.001	.061	.474	.465
320.	.947	.029	.024	.997	.002	.001	.064	.474	.462
330.	.954	.026	.020	.991	.008	.001	.067	.473	.461
340.	.950	.031	.019	.998	.001	.001	.067	.474	.459
350.	.939	.035	.026	.996	.002	.001	.065	.475	.459
360.	.937	.035	.028	.994	.004	.002	.063	.477	.460
370.	.931	.039	.029	.993	.005	.002	.061	.478	.461
380.	.924	.041	.035	.996	.003	.002	.062	.478	.460
390.	.942	.033	.025	.987	.008	.005	.064	.476	.459
400.	.952	.026	.022	.993	.005	.003	.061	.478	.461
410.	.949	.025	.026	.988	.008	.004	.055	.481	.464
420.	.951	.026	.023	.991	.006	.003	.052	.484	.463
430.	.956	.024	.020	.986	.009	.005	.051	.484	.465
440.	.951	.027	.023	.983	.011	.006	.050	.485	.465
450.	.961	.021	.018	.984	.010	.005	.048	.485	.466
460.	.948	.022	.030	.977	.015	.008	.048	.485	.467
470.	.938	.030	.031	.994	.004	.002	.047	.486	.467
480.	.943	.027	.029	.980	.013	.007	.046	.486	.468
490.	.945	.027	.028	.982	.012	.006	.046	.485	.469
500.	.945	.029	.026	.980	.013	.007	.047	.486	.468

Figure G.8 Detailed Monte Carlo Statistics Data (Part 3.Weighting Factor Information)

03/19/78 1M191111 VARGUS 03734A190 000373 10 700 DATE 031978 PAGE 204

GATED CONFIGURATION: TWO MILE SPACING

AVERAGE AFTER 10 TRIALS PAGE 6

	DESIRED HEADING				PILOT RUDDER COMMAND				HELMSMAN RUDDER COMMAND				ACTUAL
	ACTUAL AVG	ABS VALUE	SQUARED	CHANGES	ACTUAL AVG	ABS VALUE	SQUARED	CHANGES	ACTUAL AVG	ABS VALUE	SQUARED	CHANGES	RUDDER
0.	85.50	85.50	7310.79	.0	1.00	1.00	5.00	.0	.74	1.77	6.14	.0	.00
10.	85.50	85.50	7310.79	.9	1.00	1.00	5.00	.5	1.08	1.35	5.34	1.0	.74
20.	85.50	85.50	7310.79	.9	.00	.00	.00	.6	-.08	.08	.06	1.0	1.05
30.	85.50	85.50	7310.79	.9	.00	1.00	5.00	.2	.00	1.15	5.11	1.0	.08
40.	85.50	85.50	7310.79	.9	.00	1.00	5.00	.1	.00	1.00	5.00	1.0	.06
50.	85.50	85.50	7310.79	.9	.00	.00	.00	.1	.00	.00	.00	.1	.01
60.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.1	-.50	.50	2.50	.1	.05
70.	85.50	85.50	7310.79	.9	-1.00	1.00	5.00	.4	-.98	1.02	5.01	.5	-.43
80.	85.50	85.50	7310.79	.9	-1.00	1.00	5.00	.5	-.96	1.04	5.02	1.0	-.90
90.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.6	-.49	.59	2.54	1.0	-.95
100.	85.50	85.50	7310.79	.9	.50	1.50	7.50	.2	.47	1.63	7.55	1.0	-.51
110.	85.50	85.50	7310.79	.9	.50	1.50	7.50	.7	.44	1.70	7.61	1.0	.44
120.	85.50	85.50	7310.79	.9	-.50	1.50	7.50	.7	-.73	1.73	7.75	1.0	.44
130.	85.50	85.50	7310.79	.9	.00	1.00	5.00	.2	-.19	1.19	5.14	.7	-.57
140.	85.50	85.50	7310.79	.9	.00	1.00	5.00	.1	-.02	1.16	5.09	.8	-.19
150.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.2	-.62	.62	2.57	1.0	-.04
160.	85.50	85.50	7310.79	.9	.00	2.00	10.00	.8	-.05	2.05	10.02	.8	-.54
170.	85.50	85.50	7310.79	.9	.00	2.00	10.00	.5	.00	2.00	10.00	.7	-.02
180.	85.50	85.50	7310.79	.9	.00	2.00	10.00	.5	-.05	2.05	10.02	.5	-.00
190.	85.50	85.50	7310.79	.9	-1.50	1.50	7.50	.6	-1.50	1.50	7.50	.8	-.04
200.	85.50	85.50	7310.79	.9	-1.00	1.00	5.00	.9	-1.04	1.07	5.03	.9	-1.30
210.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.7	-.46	.54	2.51	.7	-1.03
220.	85.50	85.50	7310.79	.9	.00	1.00	5.00	.3	.07	1.07	5.05	.7	-.49
230.	85.50	85.50	7310.79	.9	.50	1.50	7.50	.7	.54	1.54	7.51	.7	.09
240.	85.50	85.50	7310.79	.9	.00	3.00	15.00	.4	.03	3.03	15.01	.9	.52
250.	85.50	85.50	7310.79	.9	.00	3.00	15.00	.4	.00	3.00	15.00	.8	.15
260.	85.50	85.50	7310.79	.9	-.50	3.50	17.50	.3	-.47	3.53	17.51	.4	.02
270.	85.50	85.50	7310.79	.9	.00	3.00	15.00	.5	.00	3.00	15.00	.9	-.40
280.	85.50	85.50	7310.79	.9	.00	2.00	10.00	.6	.00	2.00	10.00	.6	-.01
290.	85.50	85.50	7310.79	.9	.00	2.00	10.00	.5	.00	2.00	10.00	.5	.05
300.	85.50	85.50	7310.79	.9	-.50	1.50	7.50	.6	-.45	1.55	7.52	.6	.01
310.	85.50	85.50	7310.79	.9	-1.00	1.00	5.00	.2	-1.00	1.00	5.00	.6	-.39
320.	85.50	85.50	7310.79	.9	-1.00	1.00	5.00	.9	-1.00	1.00	5.00	.9	-.92
330.	85.50	85.50	7310.79	.9	-.50	.50	2.50	1.0	-.50	.50	2.50	1.0	-.99
340.	85.50	85.50	7310.79	.9	.00	.00	.00	.3	.00	.00	.00	.3	-.52
350.	85.50	85.50	7310.79	.9	.50	.50	2.50	.1	.50	.50	2.50	.1	-.02
360.	85.50	85.50	7310.79	.9	.50	.50	2.50	.4	.55	.55	2.53	.5	.48
370.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.5	-.44	.56	2.54	.6	.54
380.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.3	-.50	.50	2.50	.6	-.30
390.	85.50	85.50	7310.79	.9	.50	2.50	12.50	.3	.50	2.50	12.50	.3	-.47
400.	85.50	85.50	7310.79	.9	2.00	3.00	15.00	.6	2.00	3.00	15.00	.6	.51
410.	85.50	85.50	7310.79	.9	1.00	2.00	10.00	.9	1.00	2.00	10.00	.9	1.94
420.	85.50	85.50	7310.79	.9	.50	2.50	12.50	.9	.50	2.50	12.50	.9	1.13
430.	85.50	85.50	7310.79	.9	.50	2.50	12.50	.8	.50	2.50	12.50	.8	.58
440.	85.50	85.50	7310.79	.9	.50	2.50	12.50	.8	.50	2.50	12.50	.8	.56
450.	85.50	85.50	7310.79	.9	.50	2.50	12.50	.4	.50	2.50	12.50	.4	.56
460.	85.50	85.50	7310.79	.9	.50	3.50	17.50	.3	.50	3.50	17.50	.3	.51
470.	85.50	85.50	7310.79	.9	.50	3.50	17.50	.6	.50	3.50	17.50	.6	.55
480.	85.50	85.50	7310.79	.9	.50	3.50	17.50	.6	.50	3.50	17.50	.6	.56
490.	85.50	85.50	7310.79	.9	-.50	1.50	7.50	.8	-.50	1.50	7.50	.8	.51
500.	85.50	85.50	7310.79	.9	-.50	.50	2.50	.9	-.50	.50	2.50	.9	-.32

Figure G.9 Detailed Monte Carlo Statistics Data (Part 4.Pilot/Helmsman Information)

```
03/19/78  1M141111 VARGUS 0373AAT90    000373        10    700                    DATE 031978      PAGE  207


                         SCI(VT) NAVAID SYSTEM EVALUATION MODEL

                 STATISTICS SUMMARY     CASE: GATED      CONFIGURATION: TWO MILE SPACING

CROSS TRACK ESTIMATION STATISTICS                  ALONG TRACK ESTIMATION STATISTICS

AVERAGE ESTIMATION ERROR                 10.7      AVERAGE ESTIMATION ERROR                 105.3
AVERAGE ABSOLUTE VALUE OF ERROR          54.5      AVERAGE ABSOLUTE VALUE OF ERROR          184.4
ERROR STANDARD DEVIATION                 69.0      ERROR STANDARD DEVIATION                 190.6
RMS ESTIMATION ERROR                     69.9      RMS ESTIMATION ERROR                     217.8


HEADING RATE ESTIMATION STATISTICS                 CROSS TRACK PERFORMANCE

AVERAGE ESTIMATION ERROR              -.00009      AVERAGE CROSS TRACK POSITION                .2
AVERAGE ABSOLUTE VALUE OF ERROR        .00051      CROSS TRACK POSITION ST. DEV.             86.7
ERROR STANDARD DEVIATION               .00082
RMS ESTIMATION ERROR                   .00082
AVERAGE ANTICIPATED ST. DEV.           .02714


PILOT-VESSEL PERFORMANCE

AVERAGE RUDDER                          -.060
RUDDER STANDARD DEVIATION                .547
RMS RUDDER VALUE                         .551
AVERAGE NO. OF RUDDER COMMANDS                              62.100
AVERAGE PERCENT OF TIME VESSEL UNDER ACTIVE PILOT CONTROL   26.281
```

496X

Figure G.10 Overall Monte Carlo Summary

496 blank.

APPENDIX H
DECISION/CONTROL PARAMETER SELECTION AND SENSITIVITY

H.1 DEFINITION OF DECISION/CONTROL TRACK-KEEPING PARAMETERS

As presented in Section 3.3.3.1 and Appendix F, the mariner track-keeping decision/control functions (whether in a turn or on a straight track segment) are nonlinear in their implementation, consisting of a number of "decision regions," each characterized by its own linear feedback control law. These decision regions and particular control laws are defined by threshold parameters (PDB1 and PDB2) as shown in Figure H.1.

Entry to and exit from the various control regions are governed by decision threshold expressions of the following general form:

$$|\widehat{CTD} + KTC \cdot \hat{\dot{CTD}}| > PDB \qquad (H.1)$$

where

$\widehat{CTD}$ is the cross track deviation estimate;

$\hat{\dot{CTD}}$ is the cross-track deviation rate estimate;

PDB is the threshold value for the respective region (i.e., PDB1 or PDB2); and

KTC is the "prediction" parameter for the cross-track deviation.

The Region 1 control law ("steer to desired heading") also applies a threshold of this type, except that the threshold is based on estimates of the heading error ($\hat{H}_e$) and heading rate error ($\hat{\dot{H}}_e$):

$$|H_e + KTH \cdot \dot{H}_e| > HDB \qquad (H.2)$$

where

HDB is the heading threshold and
KTH is the heading prediction parameter

Inside the heading threshold, no control action is taken by the pilot, and he permits the helmsman to steer to commanded heading.

APPENDIX H

DECISION/CONTROL PARAMETER SELECTION AND SENSITIVITY

H.1 DEFINITION OF DECISION/CONTROL TRACK-KEEPING PARAMETERS

As presented in Section 3.3.3.1 and Appendix F, the mariner track-keeping decision/control functions (whether in a turn or on a straight track segment) are nonlinear in their implementation, consisting of a number of "decision regions," each characterized by its own linear feedback control law. These decision regions and particular control laws are defined by threshold parameters (PDB1 and PDB2) as shown in Figure H.1.

Entry to and exit from the various control regions are governed by decision threshold expressions of the following general form:

$$|\hat{CTD} + KTC \cdot \hat{\dot{CTD}}| > PDB \qquad (H.1)$$

where

$\hat{CTD}$ is the cross track deviation estimate;

$\hat{\dot{CTD}}$ is the cross-track deviation rate estimate;

PDB is the threshold value for the respective region (i.e., PDB1 or PDB2); and

KTC is the "prediction" parameter for the cross-track deviation.

The Region 1 control law ("steer to desired heading") also applies a threshold of this type, except that the threshold is based on estimates of the heading error ($\hat{H}_e$) and heading rate error ($\hat{\dot{H}}_e$):

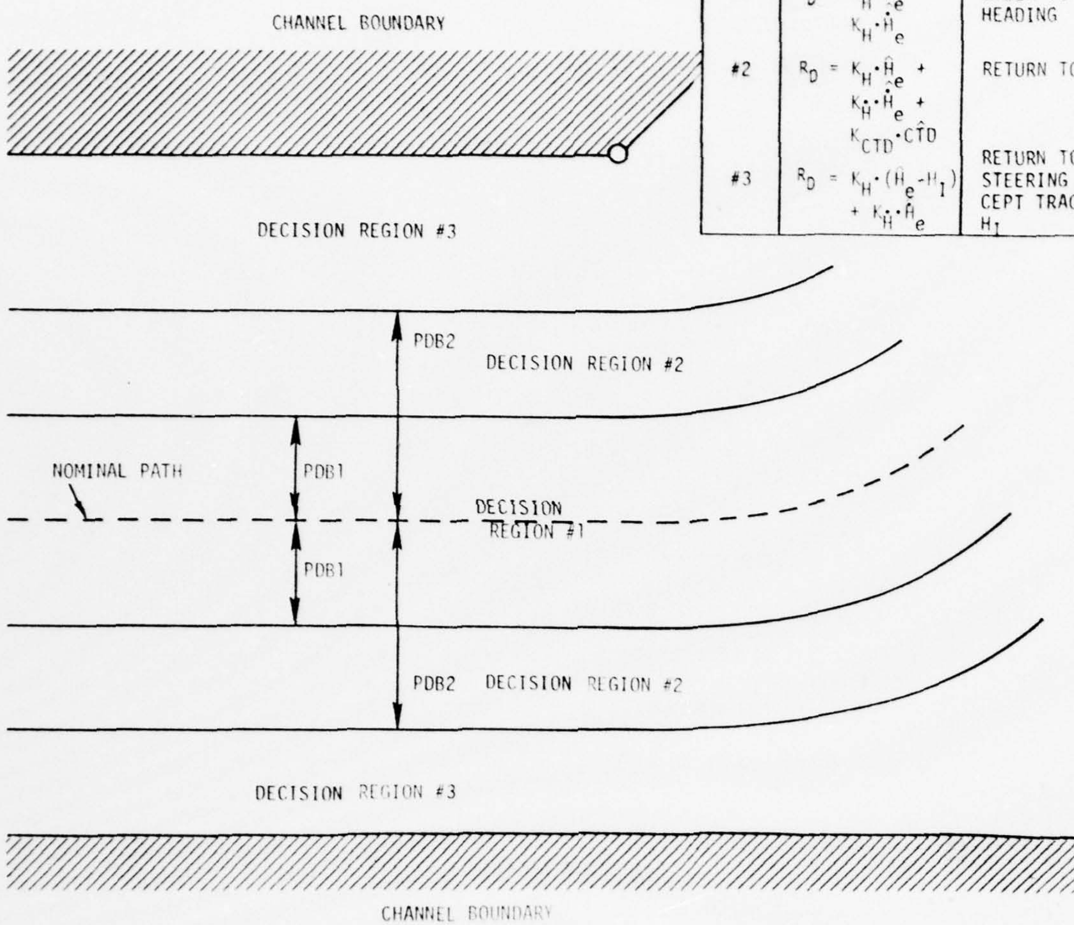
$$|H_e + KTH \cdot \dot{H}_e| > HDB \qquad (H.2)$$

where

HDB is the heading threshold and

KTH is the heading prediction parameter

Inside the heading threshold, no control action is taken by the pilot, and he permits the helmsman to steer to commanded heading.



DEC. REGION	CONTROL LAW	CONTROL OBJECTIVE
#1	$R_D = K_H \cdot \hat{H}_e + K_{\dot{H}} \cdot \hat{\dot{H}}_e$	STEER TO DESIRED HEADING
#2	$R_D = K_H \cdot \hat{H}_e + K_{\dot{H}} \cdot \hat{\dot{H}}_e + K_{CTD} \cdot \hat{CTD}$	RETURN TO TRACK
#3	$R_D = K_H \cdot (\hat{H}_e - H_I) + K_{\dot{H}} \cdot \hat{\dot{H}}_e$	RETURN TO TRACK BY STEERING TO INTERCEPT TRACK AT ANGLE H_I

Figure H.1 Mariner Model Decision Regions and Control Laws

Within each control region, the decision/control logic applies a linear feedback control law of the following form:

$$R_D = K_{\dot{H}}(\hat{\dot{H}} + \frac{K_H}{K_{\dot{H}}}(\hat{H}_e - H_I) + \frac{K_{CTD}}{K_{\dot{H}}}\hat{CTD}) \qquad (H.3)$$

where the K's are controller gains and H_I is the desired track intercept angle. The Region 3 control law is implemented by setting $K_{CTD}=0$ in the above equation. The Region 2 law results from setting $H_I=0$; and the Region 1 law from setting both $K_{CTD}=0$ and $H_I=0$.

A summary of the mariner decision/control parameters is presented in Table H.1. The rationale for the structure of parameter interrelationships and analysis results which support the selection of numerical values are presented in the following sections.

H.2 RATIONALE FOR DECISION/CONTROL LOGIC STRUCTURE

The Region 1 control law -- "steer to desired heading" -- is characterized by the heading preview parameter KTH and the linear feedback law (Eq. H.3) with $K_{CTD}=0$ and $H_I=0$.

From an operator modeling point of view, Region 1 represents the least amount of mental and control workload due to the relative simplicity of the structure as compared to Regions 2 and 3. This requires the fewest variables for both the decision and control law models. The region is characteristic of the human operator in a regulatory tracking task; i.e. attempting to minimize small deviations (in this case heading errors) from the nominal trajectory. It is well known that the gain ratio $K_H/K_{\dot{H}}$ should approximate the vessel's dynamic time constant; i.e. the operator applies feedback that approximately cancels these dynamics. This is commonly referred to as lead information. Using such lead information requires sufficient accuracy in estimating heading rate that spurious rudder commands are prohibited, and noise rejection is consequently a desired property of the compensation gains as derived in Section H.3.

Table H.1

Pilot/Helmsman Decision and Control Parameters

PROGRAM NAME	DESCRIPTION	APPROXIMATE EXPRESSION	NUMERICAL VALUES USED 8 kts	12 kts	COMMENTS
Decision Threshold Parameters					
PDB1	Pilot cross-track deviation threshold--level 1 (linear cross-track feedback law).	1/4 (W/2)	100 ft.	100 ft.	Threshold based on projected cross-track KTC seconds into the future.
PDB2	Pilot cross-track deviation threshold--level 2 (return to track at desired intercept angle)	1/2 (W/2)	200 ft.	200 ft.	Threshold based on projected cross-track KTC seconds into future. Law used for return to track from large deviations.
KTC	Pilot cross-track preview (prediction) parameter--levels 1 and 2	2 L/U	120 sec.	80 sec.	Projected cross-track ($\hat{CTD}$) (= $CTD + KTC \cdot \dot{CTD}$) is compared to threshold PDB1 and PDB2.
HDBP	Pilot heading error threshold	2 deg	2 deg.	2 deg.	Threshold based on projected heading error KTHP seconds into the future.
KTHP	Pilot heading error preview (prediction) parameter	2 L/U	120 sec.	80 sec.	Projected heading error (= $\hat{H} + KTHP \cdot \dot{H}$) is compared to threshold HDBP.
HDBH	Helmsman steering (heading error) decision threshold	0.5 deg	0.5 deg.	0.5 deg.	Similar to pilot's parameter HDBP
KTHH	Helmsman heading error preview (prediction) parameter	60 sec	60 sec.	60 sec.	Similar to pilot's parameter KTHP
TWAIT	Amount of time pilot waits after achieving benign state before turning course steering control back over to helmsman	30 sec	30 sec.	30 sec	Pilot also supplies desired heading angle to helmsman

Table H.1 (Continued)

PROGRAM NAME	DESCRIPTION	APPROXIMATE EXPRESSION	NUMERICAL VALUES USED 8 kts	12 kts	COMMENTS
Control/Steering Law Gains					
GPHD	Pilot level 1 (Decision Region 2) return-to-track control law gains: δ_D=GPCTD·$\hat{CTD}$+GPH·$\hat{H}_e$+GPHD $\hat{\dot{H}}_e$	1.2 L/U	68.29	45.78	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GPH		.02 GPHD	1.374	0.9156	
GPCTD		.00015625 x GPHD/U	.000805	.000358	
GPHD	Pilot level 2 (Decision Region 3) and steering law gains: δ_D=GPH ($\hat{H}_e$-H_I)+GPHD·$\hat{\dot{H}}_e$	1.2 L/U	1.374	.9156	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GPH		.02 GPHD	.000805	.000358	
GHH	Helmsman steering law gains: δ_D=GHH·H_e+GHHD·$\dot{\hat{H}}$	0.75 L/U	42.93	28.61	Values depend on vessel data and velocity -- nominal based on 80,000-ton tanker
GHHD		.0333 GHHD	1.43	.9528	
H_I	Desired track intercept angle for pilot	constant	5°	5°	Currently assumed constant. This will be updated as appropriate in Phase II.
H_E	Heading error	$\hat{H}$-H_D	variable	variable	Actual vessel heading ("compass reading," not direction of travel) minus desired heading. The desired heading is determined by the pilot model as a function of track orientation and crab angle.

W = channel width
U = Ship speed
L = Ship length

The structure of the Region 1 threshold is similar to that of the control law, again because of its simplicity and the fact that no additional processing by the operator is required. Thus, the previous parameter KTH would, in a nominal configuration, be approximately equal to $K_{\dot{H}}/K_H$. Previous studies of a helmsman model postulated and validated from experiments [6] have identified a value of KTH of about 100 seconds. Obvious extensions to this structure to be considered in Phase II would relate this preview time constant to visibility conditions (fog, day/night, etc.) and environmental stress factors. In fact, some previous human operator models characterize workload as a function of preview time. Decreased preview time corresponds to increased workload; the causality, however, has not been established.

The Region 2 control law -- "return to track" -- is characterized by the cross-track preview parameter KTC and the linear feedback law (Eq. H.3) with $H_I=0$. The predicted cross-track is compared to an "acceptable" limit established in the mariner's mind. This limit is currently a constant in the PON model, but extensions include varying this parameter as a function of environmental factors, similar to that for Region 1.

Inclusion of the additional CTD term in the feedback control law is clear from an operator modeling point of view. First, an increase in the stress level is implied as the system transitions from Region 1 to Region 2. (The cross-track deviation is increased, implying increased concern of the mariner to adequately control the ship.) Hence, additional processing is appropriate. The estimated function must provide an additional variable to estimate (in this case, $\widehat{CTD}$); thus, additional mental processing is required. The subsequent system performance is improved with this control strategy due to the fact that additional phase lead is introduced from a transfer function point of view, which is the correct strategy. This points out the always conflicting requirements in terms of system performance versus increased mariner workload. Performance

is improved; however, the mariner pays a penalty in increased workload -- in this case mental workload to obtain cross-track deviation.

Another way to view the increased processing requirements is to observe that to first order:

$$\dot{CTD} \approx V \sin H_e$$

where V is the vessel speed and H_e is heading error. For small values of H_e, this equation may be approximated by:

$$\dot{CTD} \approx V H_e$$

or

$$CTD = V \int H_e \, dt$$

assuming constant speed. Thus, the mariner is forced to process (integrate) heading over a sufficient time interval to obtain CTD. The control law for Region 2 can then be characterized by a term proportional to H_e, $\dot{H}_e$, and $\int H_e \, dt$. In human operator technology, this proportional-integral-derivative control model structure has been used with much success [15].

Region 3 presupposes a high stress situation for the mariner, which is reflected in an immediate return to track control objective. This is consistent with a precognitive strategy in which the mariner recalls a fixed open-loop control law, namely, "steer to the desired path with a nominal intercept angle."

H.3 PARAMETER SELECTION AND SENSITIVITY STUDIES

Although this multi-region structure of the mariner decision/control model is highly desirable for its flexibility, its nonlinear nature greatly complicates conventional sensitivity analysis over, for example, the case of a purely linear feedback controller. Such

a sensitivity analysis must consider the threshold and prediction parameters and the effects of transitioning between control regions, in addition to control law feedback gains. While a full-scale sensitivity analysis to decision/control parameters is beyond the scope of Phase I, the parameter selection process necessitates studies which have given a good qualitative feel for which parameters are of significance and what ranges of these parameters reasonably emulate mariner performance under various conditions. The results of these parameter selection studies, summarized in Table H.1, are presented below for the various control regions.

H.3.1 Steering Response

In order to study pilot response as a function of steering parameters, an off-line simulation was set up. The simulation uses the full vessel dynamics model, but simplified decision/control logic and a "perfect" estimator. Heading error steps were applied to various parameter sets. The following parameters were varied:

HDB: Steering deadband

KTH: Steering preview time

$K_{\dot{H}}/K_H$: Steering gain ratio

Varying HDB did not appreciably affect the dynamic response to the heading error steps. It did, however, govern steady-state steering tolerance, as expected. The values of 0.5 degrees and 2.0 degrees were selected for the helmsman and pilot steering deadbands, respectively. These values are conservative (high) compared with the literature [6], in which the parameter ranges from 0.1 to 2 degrees. The deadband value is assumed constant in Phase I studies. The literature supports this, as well as various other functional forms. An expression derived from the Delft work shows particular promise:

$$HDB = q(1 + p\ |\hat{H}_e|)$$

where p and q are empirically derived parameters. An expression of this type will be considered for the Phase II model.

The steering preview time and gain ratio were varied in a mutually consistent manner, with results summarized in Table H.2. As expected, increasing these parameters decreased system bandwidth, causing a more sluggish but less oscillatory response with less overshoot. Reduced overshoot and enhanced noise rejection properties associated with the longer preview time and higher ratio of $K_{\dot{H}}$ to K_H led to the selection of the latter set of values. The steering response to a five degree initial heading error at 8 knots is shown in Figure H.2.

Table H.2

Summary of Steering Preview and Gain Ratio Studies

CASE	RISE TIME	OVERSHOOT
KTH = 1 · L/U $K_{\dot{H}}/K_H$ = 30	75 sec	29.4%
KTH = 2 · L/U $K_{\dot{H}}/K_H$ = 50	100 sec	21.9%

L = ship length

U = ship speed

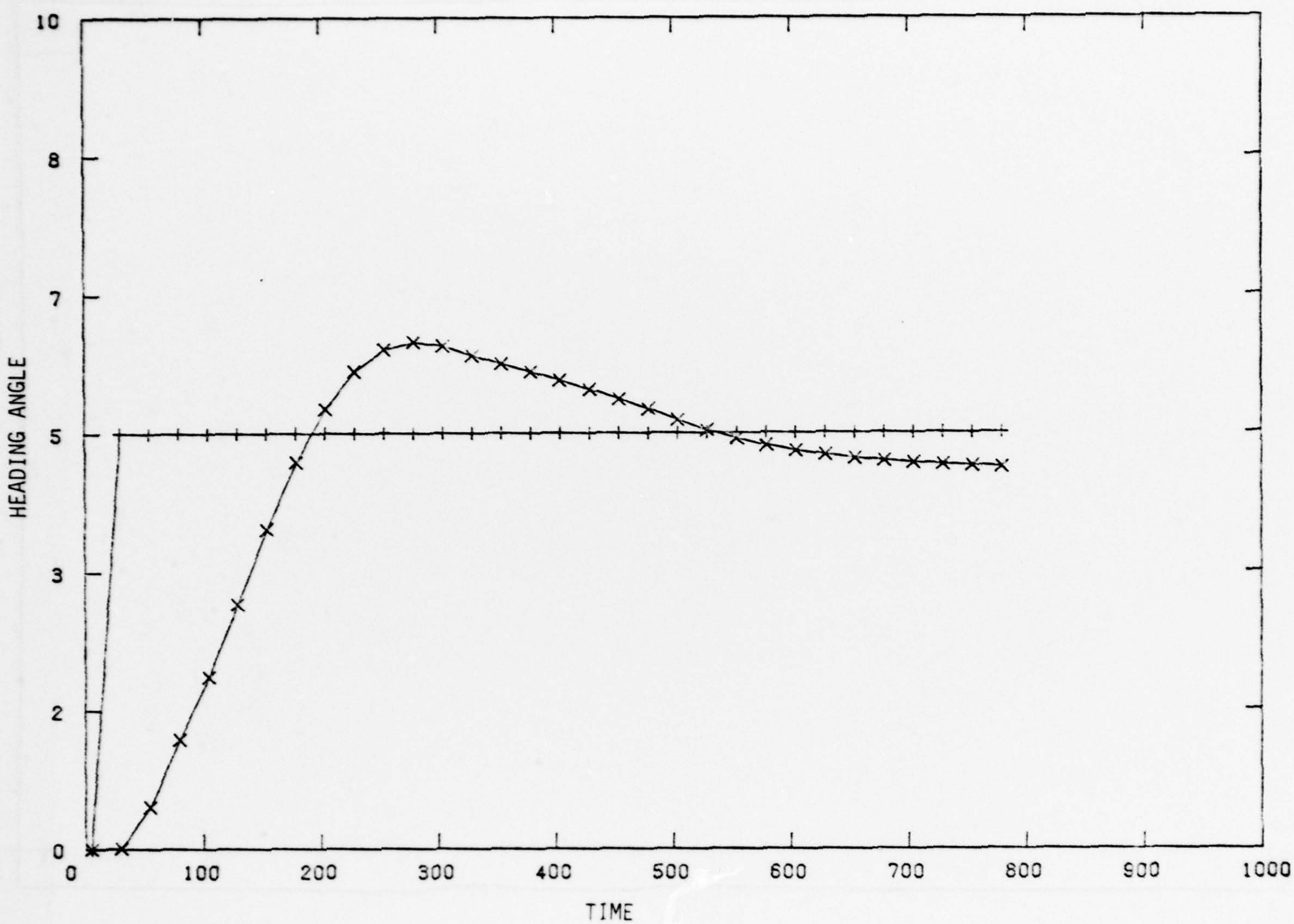


Figure H.2 Response of Region 1 Heading Control Law to 5 Degree Initial Step

H.3.2 Return to Track Response

The Region 2 return to track control law (Eq. H.3 with $H_I=0$) was examined for two different sets of decision/control parameters:

Case A: KTC = 2 L/U, $(K_{CTD}/K_{\dot{H}}) = .000242/U$

Case B: KTC = 2 L/U, $(K_{CTD}/K_{\dot{H}}) = .000156/U$

The first parameter set would theoretically exhibit a faster yet less damped response than the second, due to the larger cross-track gain ratio. This prediction is borne out by the simulation results as shown in Figures H.3 through H.6.* The Case A response is faster and more oscillatory, and calls for a greater number of rudder control actions by the pilot. To yield better damping qualities, the Case B gains were selected for the Phase I model.

* The cross-track threshold was set at 100 ft. and an initial 150 ft. cross-track error was given for these runs. A 12 kt ship speed was used.

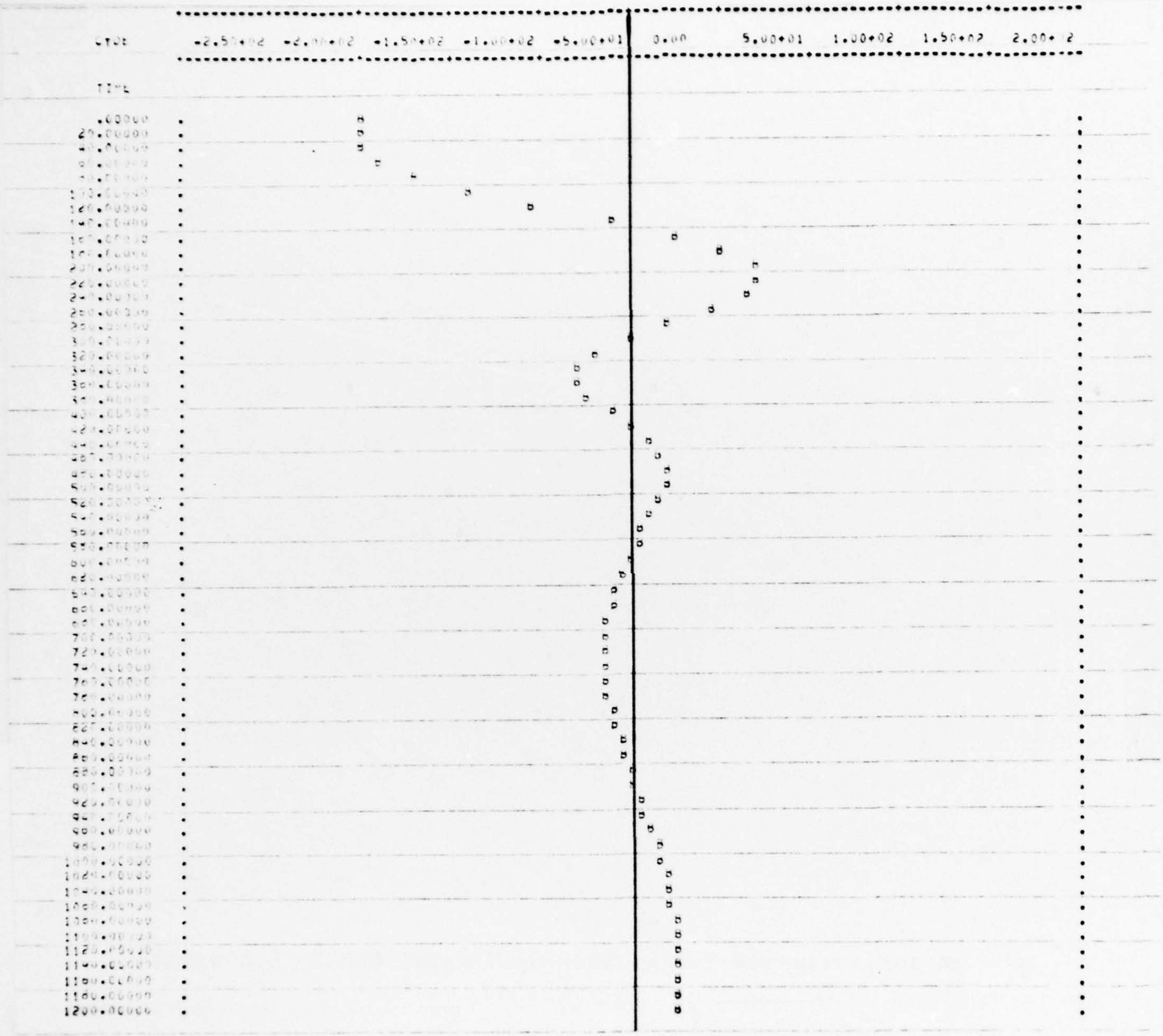


Figure H.3 Cross-Track Time History for Parameter Set A

Figure H.4 Rudder Command Time History for Parameter Set A

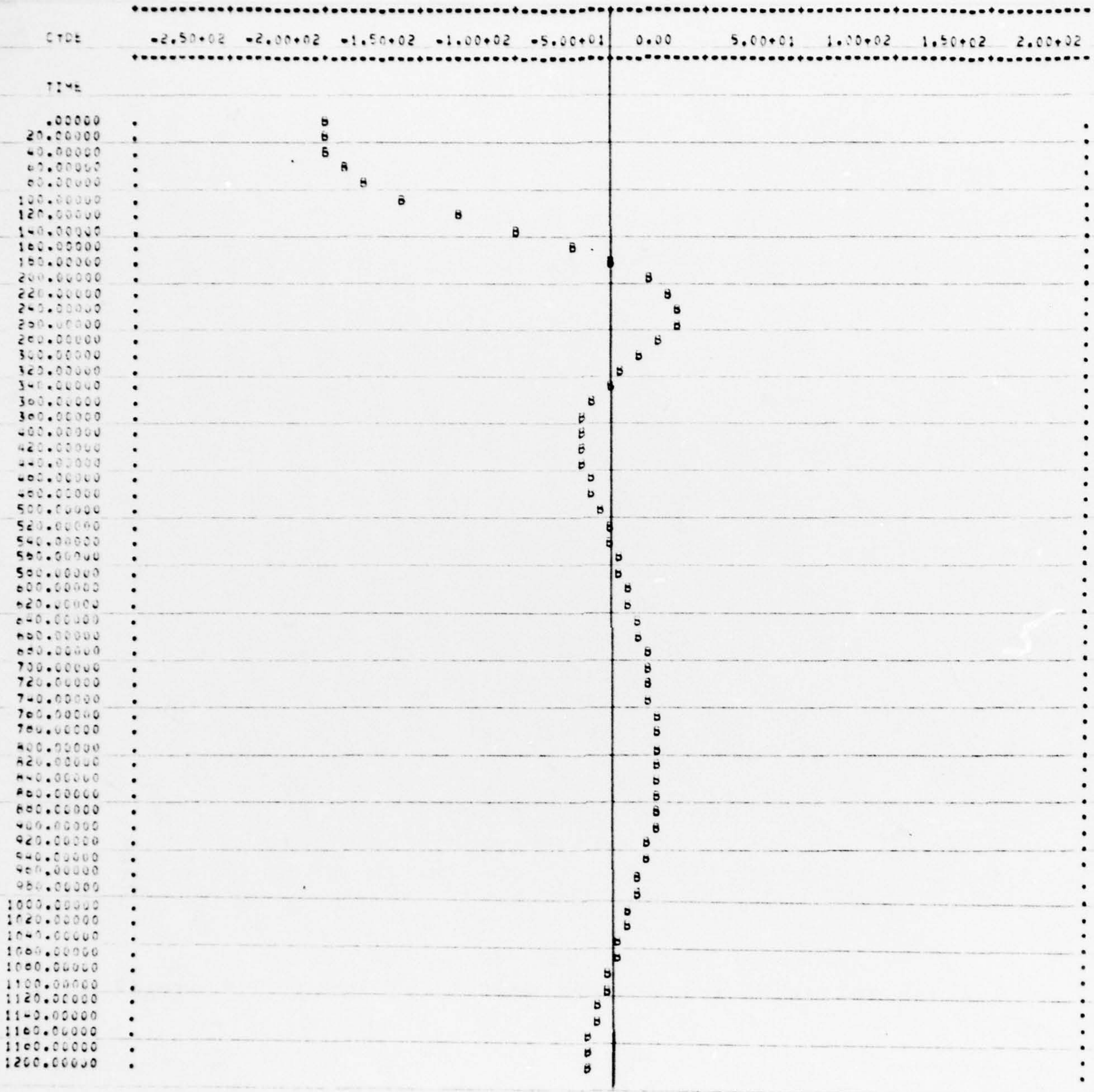


Figure H.5 Cross-Track Time History for Parameter Set B

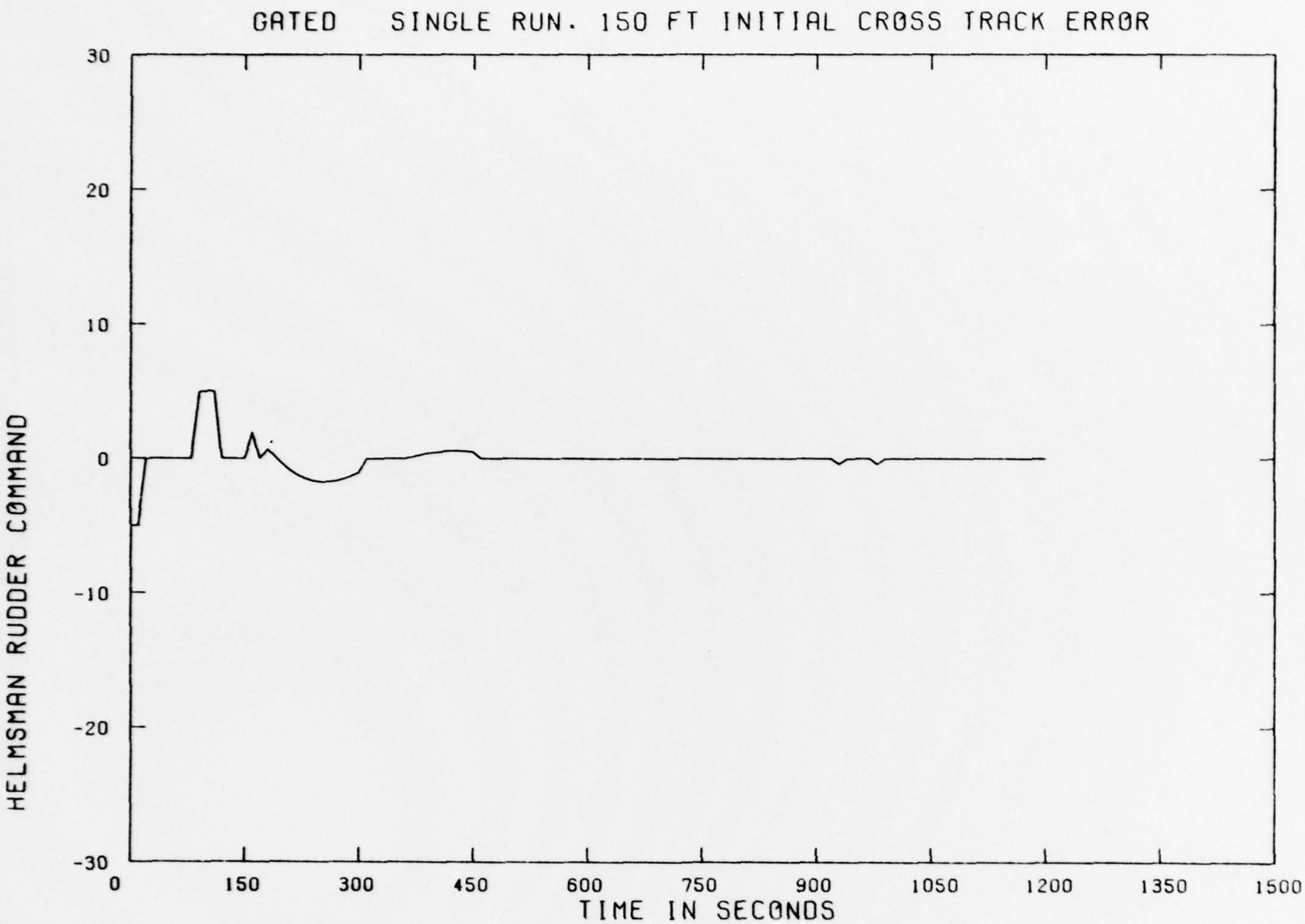


Figure H.6 Rudder Command Time History for Parameter Set B

512+ @

512 blank all